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Final report

INVESTIGATION INTO INSECTICIDAL EFFICACY AGAINST THE POTATO TUBER MOTH, *PHTHORIMAEA OPERCULELLA*

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CONTENT

SUMMARY

Fifteen potato tuber moth populations were collected in several provinces of South Africa for evaluations against registered insecticides. The tuber moth populations were mainly collected in areas where potato farmers were complaining about the effectiveness of the insecticides. All collected moth populations were reared in an insectary at ARC-Roodeplaat for two to three generations to gather enough first instar larvae for laboratory bio-assays. Survival of larvae on treated leaves was compared with untreated controls. All populations were also compared with a susceptible reference population. Resistance in the potato tuber moth against registered insecticides in South Africa could not be proven. In the laboratory, all insecticides gave absolute control against all field populations when using the recommended (100%) to 25% of the recommended field dosage. At 10% of the recommended dosage, no insecticides demonstrated significantly lower mortalities when compared to the reference susceptible population. This was true for all populations evaluated. Two case studies are examined in an effort to explain the frequent reporting of poor tuber moth control with insecticides during some years and on some farms. A section that deals with “Best practices for potato tuber moth control” is included as a separate addendum at the end of the report.

OPSOMMING

Vyftien aartappelmot populasies is versamel in verskeie provinsies van Suid Afrika vir evaluering teen geregistreerde insekdoders. Die motpopulasies is hoofsaaklik versamel in areas waar aartappelprodusente klagtes uitgespreek het oor die swak werking van insekdoders. Al die motpopulasies wat versamel was is in ‘n insektarium by LNR-Roodeplaat geteel vir twee tot drie generasies om genoeg eerste instar larwes te verkry vir laboratorium bioassays. Oorlewing van larwes op behandelde blare is vergelyk met onbehandelde kontroles en die versamelde populasies is vergelyk met ‘n vatbare verwysings-populasie. Weerstand by die aartappelmot teen geregistreerde insekdoders in Suid Afrika kon nie gevind word nie. Alle insekdoders het ‘n 100% effektiwiteit getoon teen alle populasies met die aanbevole velddosis en ook met verlaagde dosisse tot 25% van die aanbevole dosis. Met die 10% dosis het geen insekdoder betekenisvolle laer mortaliteite getoon in vergelyking met die verwysings-populasie nie. Twee gevallestudies word beskryf om die swak beheer van die aartappelmot in sommige jare en op sommige plase te verduidelik. ‘n Addendum wat handel oor “beste praktyke vir aartrappelmotbeheer” is by die verslag aangeheg.

OBJECTIVES

i) Continue the collection of tuber moth populations where possible.
ii) Continue with the rearing programs of tuber moth populations in the insectary.
iii) Continue with maintaining potato plants in glass houses for bioassays.
iii) Continue with the evaluations (bioassays) of insecticides against the tuber moth.

INTRODUCTION

The potato tuber moth *Phthorimaea operculella* (Zeller) is distributed in almost all tropical and subtropical regions of the world (Kroschel & Koch 1996), and is not only found on potatoes but also on tobacco, tomato, eggplant and other Solanaceous crops and weeds (Farrag 1998; Bennett *et al.* 1999). In South Africa, it is one of the most destructive potato pests with almost R40 million lost yearly due to its damage (Visser & Schoeman 2004). Most commercial farmers rely heavily on chemicals in order to control *P. operculella* either in the field or in storage (Keeratikasikorin & Hooper 1981; Mansour 1984) using organochlorides, organophosphates, carbamates and pyrethroids. However, during the past ten years various newer chemical pesticide groups have become available in South Africa for tuber moth control. They include a pyrrole, an oxadiazine, benzoylureas and spinosad (Nel *et al*. 2002). Foot (1974) in laboratory studies, and Nabi (1985) in field tests, reported some insecticides causing no significant reduction of pest infestation and this was thought to be the development of resistance. Champ and Shepard (1965) have reported resistance of potato tuber moth against insecticides in Australia. However, Foot (1975) reported no resistance in a study carried out in New Zealand. The occurrence of resistance in potato tuber moth is poorly known, but is believed to have been caused by inefficient mixing of pesticides, spraying not according to the label and using higher dosages than what is recommended. However, other factors may influence the effectiveness of insecticides, of which some are environmentaly related. In all potato production areas of South Africa, various insecticides are used in field spraying programs. However, the tuber moth is reported to be always present, sometimes in uncontrollable numbers. Farmers report contradictory “results” after using certain insecticides, and during some years the moth is a more severe problem than in previous years. Therefore a study was initiated to test the efficacy of insecticides registered in South African against potato tuber moth field populations, compared to a known susceptible population. The field populations were collected in various potato production areas in South Africa, and the susceptible population was obtained from the insectaries of ARC-VOPI. This study will therefore provide an indication as to which insecticides show resistance to the moth and also which geographical moth populations are affected.

An analysis of variance was performed on the data for those insecticides that showed less than 70% efficacy against at least one population at the 10% dosage. Fisher’s protected least significant difference test was performed on the combined data to establish the efficacy of insecticides against all six tuber moth populations.

MATERIAL AND METHODS

Moth populations

Fifteen potato tuber moth populations have been collected across South Africa. At the start of the project, moth populations were collected in all provinces visited, but after initial results indicated that insecticides were still effective, populations were collected only in areas where yield losses or heavy infestation were reported. It was reasonable to assume that farmers in those production areas that were not complaining about the potato tuber moth did not have a potential resistance problem. The tuber moth populations collected for this study are indicated in Table 1.

Rearing of test subjects

The rearing of the potato tuber moth formed an integral part of this project and proved to be a daunting task. The life-cycle of Lepidoptera, to which the tuber moth belongs, is a holometabolous process. That means that the life cycle involves several successive stages; each stage distinctly different from the previous stage and needing different food sources and handling techniques. To rear only one moth population involves complex handling and feeding techniques. To rear a complete life cycle of the tuber moth takes approximately 5 weeks. Because of the complexity of the rearing process, it is not practicable or feasible to split one population into more than one duplicate population to shorten the time intervals between the availability of moths. That means that the testing window period for each population is only once every 5 weeks. If one window period (e.g. the availability of eggs on a specific day) is missed, it would have only be available 5 weeks later. Personnel are not always available (sickness, leave, holidays etc.) on the exact dates that test subjects become available or sometimes other infrastructure, e.g. the availability of plants, are not synchronized with the emergence of test subjects. The rearing programs required attention on a daily basis, including Saturdays and Sundays. All of the above mentioned factors add up to very difficult circumstances under which this project was managed. To ensure its success, personnel on this project have been working every weekend since its inception. A detailed description of the rearing processes needed to reproduce the potato tuber moth and its larvae for experiments that were used in this study will be too extensive for inclusion in this report. See Visser (2004) for a detailed description of the rearing techniques of the potato tuber moth.

Table 1. The potato tuber moth populations that were collected and reared in an insectary for evaluation against insecticides.

1. Mother population
2. Highveld A
3. Highveld B
4. Highveld C
5. Highveld D
6. Ceres A
7. Ceres B
8. Sandveld
9. Eastern Free State A
10. Eastern Free State B
11. Eastern Free State C
12. Eastern Free State D (G)
13. Northern Cape
14. Limpopo
15. Eastern Cape

Insecticides

All the insecticides registered for potato tuber moth control in South Africa (Nel *et. al* 2002) were evaluated against the populations listed in Table 1. The exception was monocrotophos which was withdrawn for use as a pesticide in South Africa by the Department of Agriculture. The concentrations used in the laboratory bioassays were based on recommended dosages on the label of each insecticide. This was considered as the benchmark. Distilled water was used to prepare and dilute insecticides and also for the untreated control. Most insecticides are effective at a particular pH level, and as a result, the pH of the distilled water was corrected using a buffer (Aqua Right 5).

Bioassays

Detached leaf bioassays - larval mortality

To evaluate insecticidal efficacy against larvae of the tuber moth, a detached leaf bioassay was performed. Potato leaves were obtained from plants grown in a glasshouse, and first instar tuber moth larvae were obtained from the ARC-Roodeplaat insectary. Leaves were dipped in treatments for 30 seconds, and then air dried at room temperature for approximately two hours. Controls with leaves treated with water only were included. One treatment consisted of three plastic Petri dishes (three replicates) with one leaf in each Petri dish. An effort was made to use same-sized leaves to make useful comparisons between treatments/replicates. To facilitate the survival of the leaves in the Petri dishes, wet filter paper were put inside each Petri dish before the treated leaves were added. The filter paper in every Petri dish was checked every morning. If needed, 0,5-1 ml distilled water was added to the filter paper by means of a micro-pipette. The aim was to keep the filter paper beneath every leaf permanently wet without the presence of any free flowing water inside the Petri dishes. This proved to be a difficult task because not all Petri dishes had the same evaporation tempo, resulting in some leaves drying out much faster than others. A new technique was developed to eliminate this problem. In the place of the filter paper, water agar (15g/litre) was added to Petri dishes. The water agar was prepared one day before the experiment day by dissolving 15g of agar powder in one liter of water and sterilizing it for 15 minutes at 121^0C. First instar potato tuber moth larvae were transferred to the leaves with a fine camel hair brush. Ten larvae were transferred to every leaf in Petri dishes. Petri dishes were closed and incubated at room temperature. After 9-10 days, all treatments were evaluated by counting the number of living larvae. Because of marked differences between adult mortalities when placing adults in Petri dishes coated with insecticides, and those put in Petri dishes with treated leaves, this method of evaluating mortalities was abandoned (no mortalities were obtained when treated leaves were put in Petri dishes – the moths presumably avoided the treated leaves).

Criteria for evaluations

As elaborated in the project proposal, LD50 or LD90 tests were not an option as criteria for evaluations for a project of this scope (15 populations and 23 insecticides). Probit analysis which is used to calculate LD50 and LD90 values would have needed thousands of evaluations to complete the project. Our recommendation was therefore to use an indicator dosage to compare mortalities between each population and the reference population. The reference population (mother population) has been kept for more than 18 years in an insectary and therefore susceptible to all insecticides. To establish an indicator dosage, the recommended field dosage was used as the benchmark in all tests. Where no survival was found, the dosage was lowered until meaningful survival was found. When using insecticides at the field dosage recommended in Nel *et. al* (2002), no survival of larvae from any population against any insecticide could be found. When the dosages were lowered consecutively (50%, 25% and 10% of the field dosage), meaningful larval survival of 30% or more were only appearing at the 10% dosage level. At the 5% level, variation started to influence the results too drastically, and the 10% level was therefore taken as the indicator dosage. At this dosage the survival of larval from the different regions were compared to the reference population. Significantly better survival of a specific population (compared to the reference population) with a specific insecticide would indicate resistance of the tuber moth against that insecticide. No differences would indicate that the insecticide is still effective against that specific population.

RESULTS and DISCUSSION

Survival of larvae in all populations was zero (or close to zero) against all insecticides for the 100%, 50% and the 25% dose. The results of these evaluations are therefore not indicated in tables. At the 10% dose only certain populations showed survival of larvae against certain insecticides. Table 2 indicates the insecticides that were considered effective against all tuber moth populations (70% control or better). Table 3 indicates the insecticides that showed an efficacy of less than 70% against at least one population, and tables 4 and 5 list those populations separately.

When comparing insecticides at the 10% dosage statistically (Table 3), it is clear that methomyl and methamidophos performed the worst and profenophos and azinphos-methyl the best (for all populations combined). However, when analyzing the data for each population individually (Table 4), it is evident that this generalisation cannot be made because of differences between populations. The variance in efficacy within and between populations/insecticides therefore makes a comparison difficult between insecticides that gave a control figure of 70% or less. The only conclusion we could make is that all registered insecticides gave a 100% control when using lower dosages down to 25% of the field recommended dosage. When the dosage was lowered to 10% of the registered dosage, only those insecticides in Table 2 gave satisfactory control against all populations.

Table 5 indicates the comparisons between populations with the nine insecticides that showed less than 70% control against at least one of the nine populations. The aim of this study was to find any population that would show a statistically lower control with any insecticides compared to the reference population at a defined dosage (the indicator dosage – 10% in our study). The data in Table 5 indicates that no population showed a significantly lower control compared to the reference population. All populations showed the same or lower survival rate compared to the reference population. The reference population (mother population) always showed survival as well, therefore excluding the likelihood of resistance in any of the field populations. It therefore cannot be concluded that any population showed resistance against the potato tuber moth when using all registered insecticides at the indicator dosage of 10% of the field recommended dosage.

CONCLUSIONS

Resistance in the potato tuber moth against registered insecticides in South Africa could not be proven. In the laboratory, all insecticides gave absolute or near-absolute control against all field populations when using the recommended (100%) to 25% of the recommended field dosage. At 10% of the recommended dosage, no insecticides demonstrated significant lower mortalities when compared to the reference susceptible population. This was true for all populations evaluated.

Table 2. The insecticides registered against the potato tuber moth that gave 70% control or better against all populations tested with 10% of the recommended field dosage.

acephate
beta-cyfluthrin
bifenthrin
cartap hydrochloride
chlorphenapyr
deltamethrin
diflubenzuron
indoxacarb
lambda-cyhalothrin
lufenuron
novaluron
spinosad
tralomethrin

Table 3. The insecticides that showed an efficacy of less than 70% against at least one tuber moth population tested with 10% of the recommended field dosage. The figures are the averages for all 6 populations listed in Table 4 combined, and indicate the survival of larvae out of 10. See table 4 for results of individual populations.

Untreated control	9.2^{a}
methomyl	3.8^{b}
methamidophos	3.5^{bc}
fenfalerate	2.7^{cd}
esfenvalerate	2.6^{cd}
methidathion	2.5^{cd}
a-cypermethrin	2.4^{cd}
phenthoate	2.3^{d}
azinphos-methyl	2.0^{de}
profenophos	1.1^{e}

Means followed by the same letter in each column are not significantly different at the 5% level using Fisher's protected least significant difference test. SEM = 0.39; LSD = 1.1

Table 4. The number of first instar potato tuber moth larvae (n = 10) surviving after 9 days on treated leaves with the indicator dosage of 10% of the recommended field dosage. Comparisons of insecticides.

	Moth populations					
	1	2	3	4	5	6
Insecticide	Reference	Highveld A	E-Free State G	Highveld C(Ant)	Highveld D	Limpopo
Untreat Control	9.3a	9.7a	9.3a	8.7a	9.7a	8.7a
Methamidophos	4.7b	3.3b	1.3cd	4b	3b	4.7b
Methomyl	3bc	3.3b	5.7b	5.3b	2bc	3.7b
Fenfalerate	3.3bc	3bc	1.7cd	4.3b	1bc	2.7b
Esfenfalerate	3.7bc	2.7bcd	2cd	3.3b	1bc	3b
Methidathion	3bc	0d	3.3bc	4.3b	0c	4.3b
Alpha-cypermethrin	3.7bc	0.3cd	1.3cd	3.3b	2.7bc	3.3b
Phenthoate	2.7bc	1.3bcd	0.7cd	3.7b	3b	2.7b
Azinphos-methyl	3bc	0.3cd	0d	4b	2bc	2.7b
Profenophos	1.3c	0d	0d	0c	1.7bc	3b

Means followed by the same letter in each column are not significantly different. SEM = 0.94; LSD = 2.7

Table 5. The number of first instar potato tuber moth larvae (n = 10) surviving after 9 days on treated leaves with the indicator dosage of 10% of the recommended field dosage. Comparisons of populations.

	Insecticides									
Populations	Untreat Control	Esfenfalerate	Methamidophos	Alpha-cypermethrin	Azinphos	Fenfalerate	Methomyl	Methidathion	Phenthoate	Profenophos
1 Reference pop	9.3a	3.7a	4.7a	3.7a	3ab	3.3ab	3ab	3a	2.7ab	1.3ab
2 Highveld A	9.7a	2.7a	3.3ab	0.3b	0.3b	3ab	3.3ab	0b	1.3ab	0b
3 E-Free State G	9.3a	2a	1.3b	1.3ab	0bc	1.7ab	5.7a	3.3a	0.7b	0b
4 Highveld C(Ant)	8.7a	3.3a	4ab	3.3a	4a	4.3a	5.3a	4.3a	3.7a	0b
5 Highveld D	9.7a	1a	3ab	2.7ab	2ab	1b	2b	0b	3ab	1.7ab
6 Limpopo	8.7a	3a	4.7a	3.3a	2.7ab	2.7ab	3.7ab	4.3a	2.7ab	3a

Means followed by the same letter in each column are not significantly different. SEM = 0.94; LSD = 2.7

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ADDENDUM 1

CASE STUDIES AND POSSIBLE EXPLANATIONS FOR REPORTED POOR CONTROL WITH INSECTICIDES AGAINST THE POTATO TUBER MOTH

The findings of this study indicated that no resistance was found in any of the fifteen tuber moth populations evaluated against all registered insecticides. Most of the populations that were collected and tested originated from areas where severe tuber moth problems were reported. This included four populations from the Eastern Free State and one population from the Limpopo province. Two case studies were conducted during the course of the project in these two areas to establish possible reasons for the poor tuber moth control that farmers were reported.

CASE STUDY 1: EASTERN FREE STATE

During the summer of 2007/2008, serious yield losses were reported by farmers in the Bethlehem and Petrus Steyn production areas. Most farmers reported losses of 30% while some farmers estimated losses of up to 40%. The farmers calculated their losses by counting the number of large potato containers that were used to transport the potatoes from the field to the sorting stores compared to the number of containers that they had to use to discard the tuber moth infected tubers at the end of each day.

The farmers reported the following statistics for three consecutive years;

2006/2007	5% yield loss
2007/2008	30% yield loss
2008/2009	5% yield loss

During all three years the production practices were generally the same and the same insecticides were used. It is obvious that it is not possible for the same tuber moth population (area wise) to suddenly become resistant during one year and then become susceptible again the following year. Something else was to blame for the 30% yield loss during the 2007/2008 production season.

The only marked difference between the 2007/2008 production year and the other two years were the prevalent weather conditions. A severe drought with higher than usual temperatures was reported for the entire summer in the Eastern Free State region. The farmers in this region are mostly dryland producers, aggravating the circumstances for potato production during dry periods. Despite the negative circumstances, most potato farmers still managed to achieve a reasonable harvest. The downgrading on the sorting tables due to tuber moth infestation, however, was unexpected. On average, 30% of the total harvest was thrown away or given to cattle as feed.

It is a well known fact that the potato tuber moth prefers hot and dry conditions (Visser 2009). Drought is therefore ideal for this moth to reproduce at an optimum rate and to cause severe damage to plantings. A population explosion is usually the result with probably millions of moths and larvae present in a single field. When a pest occurs in abnormally high numbers, it is always difficult to control with even the best insecticides. No insecticide (not even the best) kills all individuals after each application – there are always a percentage of individuals left to continue the life cycle. The higher the number of individuals in a field at spraying time, the higher the number of individuals that will survive the spray. Increasing the dosages and the number of sprays later in the season (when it is realised that a huge moth population is present) is fruitless because when the larvae start moving down cracks to the tubers at the end of the season, no insecticide can control them. The sheer number of moths and their descendents in potato fields at the end of the season after a population explosion will normally result in heavy infestations at harvest time.

It was concluded that the significant increase in yield losses by the Eastern Free State potato farmers during the 2007/2008 production season was due to the prevailing drought and high temperatures. It is therefore important that farmers in drought stricken areas take extra precautions to limit the potential moth population explosions that may result at the end of such a season. All control measures should be rechecked and verified (see “best practices” lower down).

CASE STUDY 2: LIMPOPO

During the 2008 planting season, a complaint was received from a potato farmer in the Limpopo province who experienced severe infestations in a very young potato planting. According to him the application of insecticides did not help reduce the number of leaf mines and the symptoms seemed to increase weekly. Because it was unusual for a young potato field to be highly infested, an investigation was launched to find the reason for this phenomenon.

It was found that the farmer had limited usable land and followed a rotation plan by planting successive potato crops on fields very close to each other. The field that had the potato tuber moth problem very early in the season was planted at the same time as another field was harvested nearby. There was therefore a very high inoculum source very close to the newly planted field. Although the potato tuber moth is not known to migrate, they do fly for short distances and may easily reach a new field in close proximity. The first moths that arrived as the new potato plants were emerging laid eggs on or next to them and within nine days may have given rise to a severe infestation (it takes approximately nine days for a larva to make visible leaf mines). Two weeks later a new generation emerged from this early infestation, resulting in an even more severe infestation even before the middle of the season.

In this case study the farmer acknowledged his mistake and agreed that the close proximity of the fields could have been the reason for his tuber moth problem and not the insecticides that did not work properly. The extraordinary high numbers of tuber moths in his fields made it nearly impossible for the insecticides to keep their numbers low and resulted in the high infestation early in the season.

The farmer could have prevented the situation if he had planted further away from the newly harvested field. Another option could have been to spray his field with contact insecticides a few times before he harvested. This could have lowered the number of moths flying around and also may have killed some larvae that emerged from eggs that the moths kept laying on the soil. The only problem would have been the high number of pupae that are present in any potato field after harvest. Adult moths keep on emerging from pupae in the soil for very long after harvest (Visser & Schoeman 2004). This continuing source of moths close to a newly planted field can result in early infestations. The only solution to this problem is to frequently disk or rework the soil with heavy tractor equipment to expose the pupae on the surface. However, some pupae may even survive this action and it is usually not cost effective for a farmer to rework a bare piece of soil solely for moth control purposes.

ADDENDUM 2

BEST PRACTICES FOR POTATO TUBER MOTH CONTROL

The potato tuber moth is a problem world-wide wherever potatoes are grown. The pest is especially troublesome in areas with high temperatures and low rainfall. All potato production areas in South Africa are reported to have tuber moth problems. It was only the KwaZulu-Natal province that reported an annual loss of 5% or lower – the other provinces reported a 5% or higher yield loss annually (D. Visser unpublished data). Poor tuber moth control could be attributed to a variety of reasons, sometimes a complex of factors adding to regular yield losses every year. Sometimes it is not easy to pin-point the crucial weakness area in the production practises of a farmer, or shortcomings in his control strategies that may lead to poor tuber moth control. It is therefore better to always exercise good field practices relating to production techniques and control efforts to ensure a low tuber moth problem at harvest time. Control tactics against the potato tuber moth can be divided into a) chemical and b) alternative strategies. Both these strategies can again be divided into several sub-sections.

Insecticide application is currently the most widely used and most effective control strategy against the potato tuber moth. However, under certain conditions even insecticides may not control the tuber moth. This is usually when environmental conditions favour a very high reproductive rate. Eggs (Findlay 1975) and the protected pupae usually escape the effect of insecticides and, under certain conditions, this may result in huge population explosions. This normally happens in seasons when warm and dry conditions have prevailed for more than two weeks. During a year with widespread drought and high ambient temperatures the damage may increase six fold. Unfortunately, warm and dry seasons cannot be predicted accurately. The use of alternative control strategies may reduce damage if implemented on a seasonal basis.

CONTROL STRATEGIES FOR POTATO TUBER MOTH CONTROL

Chemical

1) Follow all label instructions
2) Choose the correct insecticide at the correct phase of the crop
3) Alternate insecticides with every spray or in blocks
3) Use the correct adjuvants
4) Ensure the correct pH of mixing water
5) The use of cocktails (mixing different insecticides and adding fungicides)
6) Correct application equipment
7) Calibration and maintenance of equipment

Alternative strategies

1) Correct ridging
2) Relying on natural insect predators and parasitoids (biological control)
3) Timing of planting/harvest
4) Planting isolation
5) Rotation
6) Use of clean, uninfested, seed
7) Predictions by using pheromones and/or scouting
8) Sanitation
9) Tillage
10) Elimination of nearby inoculum
11) Resistant cultivars and GMOs

CHEMICAL CONTROL

1. Label

Every insecticide is accompanied by a label, in a separate booklet or information printed on the container. All the information needed to use the insecticide should be found on the label. The information and instructions on the label are enforceable by Act 36 of 1947 and is administered by the National Department of Agriculture. The label forms a contract between the manufacturer and user, and forces the user to abide by all the instructions on the label. That also means, that if the specific pest or crop that the user wants to control/treat is not listed on the label, it would be illegal to use that product even if it is registered for use on the specific pest on a different crop. If the label does not list a specific pest or crop, it means that that pest and/or crop was not evaluated or else a registration was refused for safety or efficacy reasons on that specific crop/pest. The label is therefore a kind of insurance that the product is effective, and is safe to use, on all crops/pests listed on the label. It is therefore not only illegal to us a pesticide if the label does not indicate the crop or pest, but the product is then also not certain to be effective against the intended pest. It must be noted that certain household packs are designed for use by home gardeners and that the concentration of the active ingredients may differ from those intended for commercial farmers. Always compare the concentration of the active ingredient that is indicated next to it on the label-face (e.g. 30 mg/l) and the accompanying dosage with other insecticides that may contain the same active ingredient. The household packs usually contain a much lower concentration and lower recommended dosage than the commercial farm products.

2. Choose the correct insecticide at the correct phase of the crop

The chemical composition of an insecticide will determine its mode of action. Modes of action include contact, stomach, systemic, translaminar (moving into the leaf on which it lands) and fumigating properties. Most insecticides display a combination of some of these properties. Contact insecticides kill insects on contact or when they walk over a treated surface, while stomach insecticides kill insects when a portion of a product is eaten that contained residues of the insecticide. Translaminar insecticides move (or are absorbed) into the leaf where they land, while systemic insecticides completely penetrate the plant and move with the phloem or xylem to other parts of the plant. Systemic insecticides are therefore present within plants and will kill insects when they consume such treated plants. Contact and stomach insecticides may be sprayed during all times of plant growth. Systemic or translaminar insecticides work better during the active growing period of the crop when fluids are still actively moving into the foliage.

3. Alternate insecticides with every spray or in blocks

Insecticides are placed into groups according to their chemical composition. Insecticides in the same group will usually kill insects in the same way (e.g. blocking certain biochemical pathways). Organophosphates and carbamates are put into the same group for this reason. Most of the other groups kill insects in their own unique way. To prevent the build up of resistance within the tuber moth, insecticides that kill insects in the same way must be alternated with one another. Insecticides in a certain group can be alternated with each spray or applied in blocks whereby one group is used for two or three times and then not again the rest of the season.

4. Use the correct adjuvants

Most insecticides contain their own adjuvants to increase the effectiveness of the active ingredient. However, sometimes extra adjuvants are recommended when the insecticides are used under certain conditions. Adjuvants are designed to do one or more of the following:

- limit evaporation of spray droplets
- improving the wetting ability especially on greasy leaves
- correct the pH of mixing water
- correct incompatibility problems
- make spray residue more weather-proof

- increase the penetration into the plant or pest
- improve droplet deposition
- increase safety to target plants
- reducing spray drift
- reduce foaming

It is not always necessary to add adjuvants when the insecticide compensates for the potential problem itself. It is best to read the label for possible information on the aspect or contact the manufacturer if in doubt.

5. Ensure the correct pH of mixing water

Some insecticides need to be mixed in water of a certain pH. Other insecticides are not sensitive and will not brake down when mixed with a too high or too low pH. If the insecticide is very pH sensitive, the label will usually recommend a buffer. A general rule, but not a fixed rule for all pesticides, is that insecticides need a lower and fungicides a higher pH. For optimum efficacy, it is always the best to consult with the manufacturer.

6. The use of cocktails (mixing different insecticides and adding fungicides)

The mixing of different pesticides (cocktails) into one tank is convenient and cost effective. Some pesticides even come premixed with different active ingredients to enhance their efficacy. Using tank mixtures saves money by reducing time, labour and fuel. Soil compacting, mechanical damage and disease transmition is also reduced with less heavy vehicles and spraying equipment moving through fields. Some pesticides are incompatible and may not be mixed in one tank. Others may need different water types (e.g. pH) while impurities in the mixing water may prevent certain pesticides from mixing. Pesticides with the same formulation usually mix easily, but a cocktail of differently formulated products usually needs extra precautions. The recommended order of mixing pesticides in the same tank is as follows;

- wettable powders
- additives such as buffers and anti-foam agents
- soluble liquids
- emulsifiable concentrates
- additives such as surfactants

Some pesticides are required to be mixed with water in a smaller container first before transferring it to the larger tank. The label instructions will usually give detailed information if special handling and mixing procedures are needed.

7. Correct application equipment

Insecticides can be applied by three basic methods, i.e. tractor mounted sprayers, aerial application and by centre pivot. The most effective of these (but not most economic), is the tractor mounted sprayer. Application by aircraft and through centre pivots is done mainly to save costs and time or when potato fields can not be accessed by tractor. Although application by aircraft and centre pivot may be effective, application by tractor mounted sprayers is still the most effective when wetting of all leaves, also the lower leaves, are an issue. Application rates of the mixtures differ dramatically between these three methods and the label or manufacturer must be consulted when in doubt.

8. Calibration and maintenance of equipment

Calibrating equipment insures that the correct prescribed dosage to kill the relevant pest is administered to the crop. Under- or overdosing is always the case with improperly calibrated equipment. Regular calibrating spraying equipment ensures;

- effective pest control
- prevention of resistance build-up
- protection of the environment and non-target organisms
- prevention of waste

- prevention of phytotoxicity or “plant burn”
- human safety
- legal compliancy

Even if the correct (legal) amount of insecticide is mixed in a tank, and the applicator does not apply the prescribed amount (e.g. 500 l per ha), then the application is illegal. Calibration goes hand-in-hand with maintenance of equipment. If an applicator is not maintained properly, it will be very difficult to calibrate accurately. All nozzles must be check before every calibration and worn or broken parts of the applicator must be replaced. If a farmer is unsure how to calibrate a specific applicator, the manufactures of the applicator or even consultants of some pesticide companies may be supportive.

ALTERNATIVE STRATEGIES

1. Ridging

Ridging is the relocation of soil between two rows to elevate the area that forms the row, covering the region where the tubers are forming under the ground. Ridging ensures that enough soil is available to avoid exposure of tubers and to prevent cracks from forming while tuber bulking is taking place. Potato tuber moth larvae cannot reach tubers when they are covered with a layer of soil of more than 5 cm deep. The only means by which infestation can take place is via minute cracks in the ground that lead to tubers. Soils can still crack when ridging is performed, but the incidence of cracks and therefore the infestation potential will be reduced. Frequent rain or irrigation may seal some cracks, but this is not always the case. It is surprising that potatoes planted in sandy soils, supposedly less prone to cracking, may still suffer severe losses due to the potato tuber moth. The main reason that larvae still reach tubers even when conditions do not favour cracks, is that only minute or microscopic cracks are needed as passageways for the very small larvae. Larvae are only 0.2 mm in diameter in their first instar, and unnoticeable cracks of that size form easily in soils when tubers are bulking or when wet soils dry out. Other practices relating to ridging that may help to reduce the incidence of potato tuber moth damage include planting cultivars that are not sensitive to deeper planting or those that do not produce tubers shallowly. Certain production practices, e.g. planting in double rowed beds, makes ridging more difficult than when planting in single rows with a wide row spacing.

2. Relying on natural insect predators and parasitoids (biological control)

A naturally occurring granulose virus is known to kill potato tuber moth larvae under favourable conditions. This virus infects populations when stress levels are high, e.g. when both ambient temperatures and humidity levels are high. It is simple to induce this disease in insectary-reared tuber moth populations and it seems that the virus is prevalent in most populations even if they appear healthy (Visser 2004). Although studies have been carried out to evaluate the effect of this virus on potato tuber moth larvae under field conditions (references in Capinera 2001 and Visser 2004), its obvious potential has unfortunately not led to the production of commercial products. The main reason is that infected larvae do not die before they reach the pupal stage, and damage is therefore not preventable in the treated generation.

Natural enemies may reduce tuber moth numbers in fields by a staggering 98% (Visser 2007). It is mainly two imported parasitoids, *Copidosoma koehleri* and *Apanteles subandinus,* that are responsible for potato tuber moth mortality in fields. However, a high incidence of parasitism is not always related to low levels of damage, and parasitoids are not always present in fields. Most insecticides that are used against other pests will also kill these parasitoids. Natural control by predators and parasitoids can never be guaranteed, even if it is known that these natural enemies are present in a field. Biological control may, however, be an important control strategy for organic and small scale farmers.

3. Timing of planting/harvest

Planting time for each area is usually fixed to coincide with cooler temperatures at the time of tuber initiation. However, if a farmer does have a choice, it would be advisable to choose the planting time so that the latter part of the season falls into the cooler months. The last part of the season is the time when the potato plant is sensitive to tuber moth attack due to the decrease in foliage in the field and cracking of soils. When plants are ready to be harvested, they should not be left in the soil but removed as soon as possible. Every day that a mature crop is left in the ground increases the chances of more damage by the tuber moth larvae. Little foliage is present on a mature crop, the moths keep on laying eggs on the ground and the resulting larvae will crawl over the bare soil in very high numbers searching for cracks to reach the tubers beneath the soil surface. For the same reason any harvested potatoes should never be left overnight in the fields.

4. Planting isolation

New potato fields must never be planted near a recently harvested field. Tuber moths emerge from harvested fields every day for a few months after harvest, even during the winter (Visser 2007). In a harvested field there will always be numerous “ground keepers”, tubers that were too small to be picked up by harvesters and sometimes rotten tubers that were discarded on the field. These “survival islands” can sometimes give rise to very high numbers of tuber moths. At harvest time there will also be a high number of pupae in the soil that are not killed or removed in the harvesting process. The moths that originate from these pupae, and the progeny of larvae still developing in the survival islands, can easily move to a nearby field and invade it from a very early stage onwards. It is therefore advisable to plant any new potato field as far away from the previous season’s field as possible.

5. Rotation

Crop rotation is very important to curb certain soil-borne diseases and pests like nematodes. To prevent the rapid build-up of the potato tuber moth, it is advisable not to follow potatoes with any other crop in the family Solanaceae. Important crops in this family include tomato and eggplant. It is also important not to plant these crops close to a previously planted potato field (see planting isolation above) or to follow any of the three crops with each other.

6. Use of clean, uninfested, seed

Potato seed are sometimes left in open storage for sprouting purposes. During this time infestation by moths that fly in and lay eggs on these tubers is possible. Most of the time, the farmer does not even know that his seed contain eggs or small larvae that are already mining inside the seed tubers. Planting such seed will not have a dramatic influence on the potato plant if the seed is still in good order. If some eyes of the seed are destroyed by the mining larvae, secondary eyes will sprout to take their place. The problem with planting infested seed is that an inoculum is planted with the seed. The larvae that are inside the tubers will reach the soil surface without much effort to pupate in the newly planted field. A large source of moths will therefore be present very early in the growing season that may lead to a serious infestation later in the season. There is unfortunately no registered treatment to kill any larvae inside seed tubers.

7. Predictions by using pheromones and/or scouting

Synthetic pheromones are available to monitor potato tuber moths in fields and in storage. These pheromones are so potent that it is not uncommon to find a string of moths on the wing following a person walking through a field with one of these pellets in his or her pocket. These pheromones are placed in traps to lure and catch male moths. Custom-made water pan traps whereby the capsule hangs just above the water are most effective. It must be remembered, however, that only male moths are attracted, and mass-trapping will therefore not be very effective. Mass-trapping and mating disruption, however, may be an option in potato stores. The best use of potato tuber moth pheromones is monitoring. In fields of larger than one hectare at least one trap should be placed in each quarter of the field. These traps should be inspected and cleaned on a weekly basis and the moths counted that were caught. The average number of moths caught per week should be noted down in a log book. This should give an indication of any drastic increases of decreases in moth numbers in any particular field. This type of monitoring is handy in deciding when to start a spraying program. Some farmers may decide to start spraying with the arrival of the first moth (in areas with a history of severe infestations).

Most farmers, however, use thresholds. A threshold is a predetermined number of moths caught over a predetermined period that would indicate that a certain action must be taken (action threshold). The farmer can establish his own thresholds, e.g. caution threshold, treatment threshold, economic threshold, etc. There is no fixed or scientifically calculated threshold for use by all potato farmers. Instead, each farmer must work out his own thresholds, starting with a general threshold of approximately 100 moths per week per trap. Most farmers start spraying when more than 100 moths are caught, but some farmers may decide to start spraying much earlier.

8. Sanitation

Sanitation plays an important role in reducing tuber moth numbers. The elimination of piles of culled potatoes and regular destruction of volunteer potato plants and solanaceous weed hosts is mandatory to prevent reinfestations. Sanitation is aimed at reducing moth numbers in off-seasons when potato plants in cultivated fields are not available to the pest. Practices that may directly lead to tuber infestations include: leaving heavily infested foliage in the fields after vine-pull, leaving harvested potatoes in fields overnight and discarding rotting tuber in the field during harvest.

9. Elimination of nearby inoculum

This goes hand-in-hand with sanitation. It is the process of actively searching and destroying any place where the tuber moth may hide or multiply. The two major sources of inoculum are previously harvested fields (volunteers and ground-keepers) and refuse areas where old or unusable tubers are discarded. Harvested fields should be kept clean of volunteers and ground-keepers (see tillage below). Refuse areas should be designed in such a way as to cover them with soil at least half a meter deep at least once a week when discarded potatoes are present.

10. Tillage

Reworking a field on a regular basis after harvest will not only destroy most volunteer plants and ground-keeper tubers, but may also expose and kill some pupae in the soil. Tillage with a plough or disc every week for a few weeks after harvest is recommended when a field had a severe infestation and a new field needs to be planted nearby.

11. Resistant cultivars and GMOs

There is currently no tuber moth resistant potato cultivar available anywhere in the world. Only a few lines with a degree of tolerance were announced by the International Potato Centre (CIP) in Peru, South America. These lines were, however, never improved to proper cultivar status. In South Africa, the only cultivar that seems to be less preferred by tuber moths is Vanderplank. Infested Vanderplank tubers resulted in a lower percentage pupation compared to other cultivars when reared in an insectary (D. Visser unpublished data). A new generation of “laboratory breeders” are currently investigating genetically modification whereby foreign genes are inserted into the potato plant to make it resistant against the potato tuber moth (and other pest and diseases). One such tuber moth resistant potato GMO was briefly introduced into the USA market in the nineties but voluntarily withdrawn after threats from the large food chain groups. In South Africa a 100% resistant Spunta cultivar was evaluated over a period of seven years, but permission from the government to make it available commercially was not granted (2009). Potato GMOs may play a more important role in the future as acceptance of the technology increases and other important pest and diseases become uncontrollable with conventional control strategies.