CROP PROTECTION PROGRAMME

Biology and Control of Armoured Bush Crickets in Southern Africa

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FINAL TECHNICAL REPORT

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Executive Summary

Armoured bush crickets (ABC) are destructive, sporadic pests of smallholder cereal crops in semi-arid areas of southern Africa. This project sought to develop and promote a sustainable IPM strategy against ABC, working in collaboration with smallholder farmers and the Botswana MoA.

The two principal areas of research were:
1) Population dynamics of ABC, aiming to develop an ABC outbreak forecasting system;
2) Development and testing of a range of environmentally benign ABC control measures appropriate for resource-poor farmers.

Ecological research filled in important gaps in our understanding of ABC population biology. ABC eggs were found very vulnerable to waterlogging, and soil moisture was needed only in the final stages of embryo development. High summer incubation temperatures are critical for egg development and hatching. Field studies revealed annual egg mortality of >50%, due primarily to predation by ants. Egg parasitism was rare. Ant predation was higher in fields than in *Acacia* scrub, the preferred habitat for oviposition. Females are selective in their choice of oviposition site, preferring to lay under shady bushes.

These ecological insights contributed to the development of a population model. A key element in this model is that adult fecundity and subsequent egg survival are never both high in the same season, since late rains extend vegetation growth but increase egg mortality. Consequently, years with *average* rainfall generate the biggest egg bank and the greatest likelihood of an outbreak in the following season. The model correctly predicts ABC outbreaks in Botswana over the last 5 years. It forecasts a possible outbreak in some areas in 2003, dependent on rainfall patterns in the coming season.

A farmer survey found that ABC was considered the second most damaging crop pest, just behind quelea. Farmer knowledge of ABC was generally poor. Existing control measures were considered ineffective and there was widespread, passive acceptance that nothing could be done against ABC. The project subsequently made an ABC information broadcast, repeated 4 times, on national radio. Farmers were very concerned about pesticide safety and surface application of baits was unacceptable. This forced the project to rethink its bait strategy and develop an acceptable, effective new technique, the baited trench (see below).

After systematic testing of bait formulations (8 pesticides, 6 bait carriers) for oral toxicity to ABC, the project recommended farmers should use carbaryl + sorghum bran (3g/kg) as bait against ABC. This selection takes cost and environmental considerations into account. Laboratory studies showed ABC are attracted to volatiles from fresh sorghum panicles, but not to ABC-derived odours. Sorghum panicle volatiles were analysed in detail. At the soft dough stage, two isomers of octadienone featured prominently in the blend; these substances are known to stimulate desert locusts and could well be ABC attractants.

Whilst assessing trenches as ABC traps, it was found that placing small quantities of bait inside the trench dramatically enhanced its performance. A 300mm deep trench containing teaspoons (2.5g) of carbaryl/bran bait at 3m intervals retained and killed 93% of crickets. The baited trench, deployed at field edges, now needs field testing under outbreak conditions. Farmer interest in this method is high (see below). The use of mechanised methods to reduce

labour in trench digging was considered. A basic mechanical trench digger was developed and field-tested, and promising results were obtained in preliminary trials using a modified plough to produce a steep-sided furrow.

Barrier application of fipronil spray (175g-ai/ha) around field plots, was tested under outbreak conditions. The treatment resulted in a 65% reduction in ABC, despite constant reinvasion by crickets from surrounding scrub. Barrier spraying therefore also has good potential as an ABC control method.

A study of the short and medium term effects of carbaryl/bran baited trench and fipronil barrier spray on non-target insects demonstrated that both methods had only a transient impact. Ant colonies (*Anoplolepis custodiens*) returned to normal activity levels 4-6 weeks after application in each case. It was concluded that both techniques target ABC effectively when applied just before the ABC field invasion, and do little environmental harm.

An ABC demonstration/training day provided information and training to 200 farmers and 50 extension staff attending from all parts of Botswana. 56/60 farmers interviewed afterwards stated they wanted to test out the baited trench during the next ABC outbreak.

Dissemination has been a priority. The project has so far generated 1 peer-reviewed paper, 1 lecture and 3 research posters presented at international conferences, and several research talks in UK and South African universities. There have also been 2 semi-popular articles, one information booklet and 3 information posters.

Background
This project resulted from a call for proposals by the RNRRS CPP Semi-arid PS in May 1998. Separate proposals from NRI and IACR-Rothamsted were merged at the request of the PSL and a collaborative project resulted, led by NRI. Preliminary visits to Botswana, Namibia and South Africa in December 1998 allowed detailed discussions with potential collaborators, during which it became clear that project resources would be over-stretched were the project to operate simultaneously in Namibia and Botswana, as provisionally planned. Because of its close proximity to the South African collaborators and the availability of a good PhD student from the Botswana MoA, it was decided to run all the project's field research from Sebele Research Station in SE Botswana.

Project Purpose
Semi-arid Purpose 2, Output SA203: "*Improved methods for the management of principal insect pests of cereal-based cropping systems developed and promoted where they are a major constraint to production*".

Sorghum and pearl millet are the main subsistence food crops in eastern Botswana and throughout much of southern Africa. Both crops suffer sporadic serious damage due to Armoured Bush Cricket (ABC), principally *Acanthoplus discoidalis*. It was estimated that the 1990/91 ABC outbreak in Botswana resulted in 40% losses of sorghum in those regions affected (Bashir *et al* 1991), whilst total millet yield losses to ABC in Namibia during the 1993 outbreak was estimated at 30% (Wohlleber 1996). There is general concern amongst farmers in those countries affected that ABC outbreaks are becoming more frequent and more damaging when they do occur. Hence there is a need to develop measures that farmers can use to manage this pest and thereby reduce cereal crop losses. The outputs of this project should significantly improve farmers' ability to manage this pest throughout the region, and thereby lead to improved food security and the alleviation of poverty.

Project Activities
There have been two main themes in the project's research. Activities listed below under headings 1 and 2 relate to ABC population biology, the dynamics of which are spectacularly eruptive for reasons that are poorly understood. If ABC population behaviour can be anticipated then forecasts of when and where outbreaks are likely to occur can forewarn farmers and extension services to be prepared to manage outbreaks. The research activities listed below under headings 3 and 4 relate to the development of control technologies appropriate for deployment by resource-poor farmers against ABC. In addition to research, the project has placed a strong emphasis on dissemination of information about ABC management to farmers and extension personnel. This has included radio broadcasts, articles in magazines and newspapers, numerous research presentations and a national farmers' training day (heading 5, below).

Research Activities:

1. ABC population biology

1.1 Egg diapause. Investigations on factors influencing diapause and egg hatching.

1.2 Egg mortality. A field experiment estimated the impact of egg parasites/predators.

Additional research. Oviposition site selection by female ABC.

2. Forecasting tool development

2.1 Population Model. A population model was developed to simulate the response of ABC populations to environmental perturbations.

2.2 Forecasting Tool. Using extensive environmental data in conjunction with the population model, a forecasting method for ABC outbreaks was developed.

3. Investigations into the chemical ecology of Armoured Bush Crickets

3.1 Plant Semiochemicals and ABC Attraction.. Long range attraction to potential food plants was established by bioassay, with volatiles isolated and identified.

3.2 Cricket-derived Chemical Attractants. Bioassays assessed whether ABC-derived volatiles serve as chemical attractants.

4. Improved ABC management strategies developed and promoted

4.1 Social Context. A farmer survey was carried out to assess farmers' perceptions, attitudes and current control practices against ABC.

4.2 Bait-based Methods of ABC Management.

4.2a Bait Formulation. Trials were conducted in the lab and field to establish the most effective bait formulation.

4.2b Bait Deployment. ABC movement patterns were evaluated to assess the most effective pattern of bait deployment.

4.3 Non-target Organisms. The effects of insecticidal residues on non-target organisms was assessed.

4.4 Barrier Spraying at Field Edges. The effectiveness of this technique was tested using Fipronil.

Additional research. Daily and seasonal movements of ABC in relation to habitat types
ABC foraging behaviour in sorghum and sorghum/beans intercrop
Development of trench digging tool and steep furrow plough

Training & Dissemination Activities:

5. Farmers' Day

5.1 Farmers' Day. A national farmers' training day was held at Shoshong to promote dissemination of the findings of this research project to farmers and agricultural extension staff from all regions of Botswana.

Additional activities. Training posters
Posters presented at research conferences
Powerpoint conference presentation
Dissemination articles

Outputs

1. ABC Population Biology

1.1 Egg diapause. Factors influencing diapause and egg hatching.

Many bush-cricket species allocate diapause differentially amongst eggs such that a proportion of the eggs laid will not hatch in the following season, even under favourable conditions. This is seen as a "bet hedging" strategy that promotes population survival in unpredictable environments such as semi-arid areas, where favourable early season conditions can be followed by highly unfavourable conditions and result in a population crash. A knowledge of egg diapause is clearly important to understanding ABC population dynamics.

In eastern Botswana annual rains start typically in late October. By this stage temperatures are rising following a cold dry winter. Most hatching/emergence of ABC nymphs occurs in mid-late December.

Methods.

Eggs were subjected to a range of controlled moisture/temperature regimes in the laboratory. Their subsequent development was monitored by weighing individual eggs and in some cases by destructive sampling for embryological examination.

Results.

- **Exposure to winter temperatures has no effect on % hatch, although prolonged low temperatures delay hatching**.

Typical winter soil temperatures (15^{o}C) applied for periods of 30, 60 and 90 days prior to incubation had no effect on the eggs' subsequent propensity to hatch. This indicates that egg diapause is not terminated by low temperatures alone, a situation which applies in many grasshopper species. Those eggs subjected to longer cold treatments did, however, hatch proportionately later, with the peak of hatching delayed by c.10 days for each 30 day increase in cold exposure.

- **Soil saturation kills eggs.**

Heavy rainfall can expose eggs to periods of soil saturation or even waterlogging. The effects of such exposure on egg mortality was investigated in the laboratory. Newly laid eggs (n=210), disaggregated from their pods, were subjected to two pre-incubation treatments: half were kept dry at room humidity (c.25%RH) whilst the other half were covered by 5mm of wet sand which was subsequently maintained close to saturation, for 8 weeks, before being allowed to dry out. Both egg samples were over-wintered at room humidity for 4 months and then incubated on soaked filter paper at 30^o. Those eggs that were initially kept under wet sand suffered 100% mortality, and rapidly became overgrown with fungus. In contrast, the eggs that were maintained at room humidity from laying to incubation suffered significantly lower mortality of 27% ($\chi^2_{(1\ d.f.)} = 121.6$; $P<0.001$).

These preliminary findings were followed by a subsequent study examining the effect of periods of immersion on egg survival, sampling weekly from 0 to 4 weeks. The results, illustrated in Figure 1a, show that more than 2 weeks immersion kills >60% of eggs and that 3 weeks immersion is fatal in almost all cases.

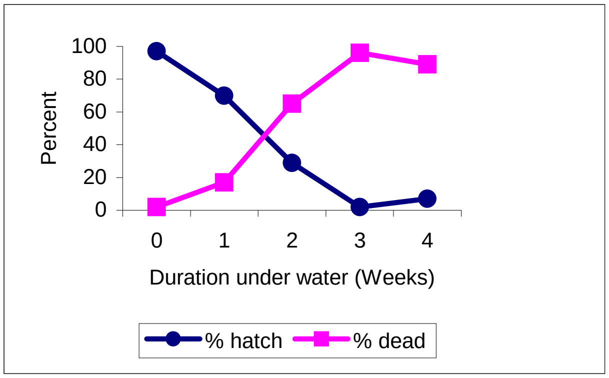


Fig. 1a. Percentage hatched and dead ABC eggs following pre-incubation submergence under water (n=450 eggs for each duration).

ABC eggs clearly cannot withstand prolonged immersion and so areas prone to water-logging will be unsuitable as oviposition sites. These insects do not occur in riparian areas, and this finding implies ABC populations will be vulnerable to periodic local extinction in areas that are subject to occasional flooding unless safe refugia exist nearby to facilitate recolonisation.

Incubation temperature affects rate of development and % hatch

After 2 months over-wintering at 20°C, 30%RH, eggs were incubated on soaked filter paper at 20°, 25° and 30°. Compared to actual soil temperatures at 5cm below surface, these incubation temperatures correspond to average winter, spring and summer soil temperatures respectively. Egg weight was monitored subsequently over 5 months.

Incubation temperature had a major bearing on the percentage of eggs breaking diapause and going on to hatch (Table 1.1), with approximately 3/4 eggs developing at 30°C. In N. Namibia, under what was effectively an outdoor temperature regime, Wohlleber (1999) found that approximately 50% of eggs hatched in the season following that in which they were laid.

Table 1.1. Effect of incubation temperature on termination of diapause.

Temperature	Sample size	% Diapause	% Hatch
20°C	292	65	35
25°C	279	45	55
30°C	246	26	74

Weight increase was most rapid in eggs incubated at 30°C, with mean hatching weight attained, on average, after 4 months. At 25°C mean hatching weight was attained, on average, after 5 months. Those eggs incubated at 20°C gained weight most slowly and none hatched within the 5 months monitoring period. Post-diapause development rates differed significantly between the different incubation temperature treatments ($P<0.001$). Incubations in these studies were conducted at constant temperatures under a 12:12 LD cycle. The effect of daily soil temperature fluctuations, which can range 10°C over 24 hours at 5cm depth in the field, on embryological development and hatching was not examined in detail. However, a higher percentage hatch was consistently obtained when eggs were incubated for rearing purposes in light bulb-lit cages, providing a fluctuating daily temperature regime, compared to constant temperature under identical 12:12 LD. This aspect requires further study.

- **Soil moisture is necessary only in the later stages of embryo development**

As the embryo develops the egg increases in weight and expands. This is especially marked in the last few weeks before hatching. In this study eggs were incubated under three moisture regimes: 1) dry, 2) dry initially then with contact water provided after 5 months to simulate natural conditions, and 3) eggs resting on damp filter paper throughout incubation. All eggs showed a small initial weight increase during the first 3 months of incubation, but dry and dry/wet lost weight again in months 4 and 5. At this point the dry/wet eggs were placed on damp filter paper: they gained further weight and hatched, doing so, on average, 3 days later than the wet sample eggs ($P<0.05$), although there was no significant difference between proportion of eggs hatching in wet and dry/wet treatments. None of the dry treatment eggs hatched. Subsequent embryological studies, sampling eggs incubated under different moisture regimes at weekly intervals, confirmed that the early stages of development continued in the absence of contact moisture, but that for development beyond katatrepsis water is necessary.

1.2 Egg mortality. Field estimates of predation and egg parasitism.

The nature and extent of mortality at each stage of the life cycle is key to understanding the population biology of ABC. Egg mortality was assessed in the following studies.

- **Annual egg mortality in SE Botswana is approximately 50%**

Egg mortality was assessed in field surveys that collected egg pods in May and December 2000 and by monitoring the survival of laboratory-laid eggs that were transplanted into the field. Both studies yielded estimates of c.50% annual egg mortality.

Table 1.2. Field surveys of egg mortality

Survey month	Sample size	Mortality (%)				Undamaged (%)
		Ant Predation	Desiccation	Rot	Parasitism	
May	2286	10	0	3	1	86
Dec	1629	42	1	5	1	51

- **The major cause of egg mortality is predation by a subterranean ant.**
- **Egg parasitism is rare.**

The subterranean ant *Dorylus helvolus* (Fig.1b) was frequently observed attacking egg pods in the soil. The worker caste (length<2mm) penetrate egg pods at a point of weakness, usually where one end of an egg presses against the pod surface. Then they systematically consume all the eggs from inside the pod. There was no indication that other ant species nor any other potential insect predators attacked ABC eggs, whilst only 1% of egg mortality was attributed to parasitism by scellionid wasps (genus *Nixonia*). Comparing the May and December surveys, it is apparent that ant predation continues throughout the year and is not confined to soft, newly laid pods. By hatching time, in December, 49% of the eggs sampled were dead; 86% of this mortality was attributed to ant predation. This is a remarkable and completely unexpected finding. Virtually nothing was known previously about tettigoniid egg mortality under field conditions.

Figure 1b. Left - *Dorylus helvolus* (soldier caste) and an ABC egg pod. A tiny worker ant is just visible in the groove, below & to the left of the pod (2mm in length). Right – ant damaged egg pods next to intact pods.

- **Egg predation by ants is higher in crop fields than in *Acacia* scrub**

The incidence of egg predation by *D. helvolus* differed between sites but was consistently higher in crop fields than in *Acacia* scrub (Table 1.3). Ant predation was also related significantly to soil type, being highest in soils with low sand content (*i.e.* soils with relatively high silt and clay content).

Table 1.3. Comparison of *Dorylus helvolus* egg predation in *Acacia* scrub and crop fields at 6 sites in SE Botswana.

Vegetation	Percent egg predation						
	Mmatseta	Letlhakane	Mmopane	Mogoditshane	Setshego	Kgaphamadi	Mean
Acacia	26.9±4.7	24.3±4.1	18.3±4.5	60.0±6.3	57.3±5.6	55.2±4.3	39.0±2.3
Crops	53.0±7.3	47.0±6.2	75.5±5.0	87.5±4.3	80.5±4.9	75.3±3.6	69.8±2.4

Although there can be little doubt that ant predation is the principal cause of egg mortality, it should be recognised that egg predation by small mammals and birds, which is sometimes observed on newly laid pods, could not be included in the present surveys. Pods eaten by small mammals (*e.g.* mongoose) are completely destroyed. Hence the absolute level of egg mortality will be higher than estimated above, whilst the % mortality due to ant predation will in reality be somewhat lower.

Ant predation accounted for similar high levels of egg mortality in an experimental study that monitored the field survival of laboratory-laid eggs. At 4 sites in SE Botswana 30 intact egg pods were transplanted into the soil below fieldside *Acacia* bushes in May, then retrieved in December and disaggregated so that individual eggs could be assessed (Table 1.4).

Table 1.4. Mortality in lab-laid eggs buried under field-side *Acacia* bushes.

Mortality Factor	Site				
	Mmatseta	Letlhakane	Setshego	Kgaphamadi	Mean %
Ant Predation	32.9±4.97	20.3±3.70	43.3±6.76	74.5±5.01	42.8±5.18
Desiccation	1.1±0.76	2.88±0.81	0.8±0.35	0.16±0.16	1.2±0.35
Rotting	5.2±0.73	5.7±2.45	3.9±1.15	6.9±2.41	5.4±0.88
Parasitism	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
Hatched	8.2±3.17	8.78±2.04	4.51±0.78	4.1±2.23	6.40±1.13
Unhatched	52.6±5.7	62.4±3.83	47.4±6.58	14.36±4.29	44.2±4.78

The overall level of egg mortality (49.5%) was almost identical to that found in the previous survey of naturally laid egg pods.

Additional Research: Oviposition studies.

Egg pod destruction has been advocated as a potential means of ABC pest management (Wohlleber 1996), but previously little was known concerning factors that influence female oviposition. Since 8/12 months of the ABC life cycle is passed in the egg stage, the selection of the egg laying site is a critical decision for females.

a) Laboratory research on ABC oviposition behaviour

The importance of soil particle type, soil moisture content and compression were investigated systematically in oviposition choice tests conducted in the laboratory cages. The principle findings were:

- **Females avoid oviposition in very sandy soils**

Females probed clay/sand, silt/sand and pure sand oviposition media equally frequently with their ovipositors, but laid significantly fewer egg pods in pure sand compared to either alternative (Table 1.5).

Table 1.5. Female oviposition preference: Soil particle type

Soil type	Mean no of egg pods laid/cage	Mean no of probe holes/cage
Clay / sand	3.06 ± 0.87	2.50 ± 0.56
Loam / sand	3.27 ± 0.76	2.61 ± 0.45
Sand	1.95 ± 0.50	2.50 ± 0.36

** soil type: P< 0.01

Given the previous findings concerning soil waterlogging and egg survival, it seems unlikely the apparent discrimination against sandy soil is related to soil drainage properties. A more likely hypothesis seems to be that finer soil particles are necessary for robust, resilient egg pods that will be resistant to ant attack, since egg pods laid in pure sand are frequently malformed and crumble easily.

- **Females prefer dry soil for oviposition**

Ten individually caged females were each provided with loam/sand oviposition media at 9 moisture levels, ranging from 0 to 20% water by weight. Nine fresh pots of media were provided in each cage, in a randomised layout, at the start of each day, for one month. The findings are summarised in Figure 1c.

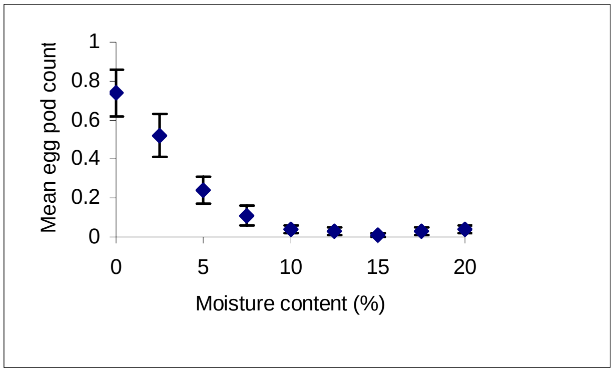


Fig. 1c. Relationship between soil moisture content and number of egg pods laid.

It is clear from the above that females prefer to oviposit in dry soil and rarely lay in soils with >5% water content. The effect of moisture content on oviposition site choice is highly significant (P<0.001, GLIM, Poisson errors, logarithmic link function).

- **Females prefer uncompacted soil for oviposition**

Three individually caged females were provided with 9 pots of loam/sand soil for oviposition comprising 3 each of uncompacted, moderately compacted and heavily compacted substrate. The number of egg pods laid was monitored Soil compaction had a significant (P<0.001) effect on female oviposition site selection, with uncompacted soil registering the highest number of egg pods, followed by medium compaction and with heavily compacted soils avoided (Table 1.6).

Table 1.6. Mean egg pod count at different compaction indices

Compaction Index	Penetrometer Depth (cm)	Mean number of egg pods/oviposition pot				
		Sampling occasion				Overall mean
		1	2	3	4	
1 (Soft)	11 – 15	0.53	0.53	0.47	0.60	0.53±0.11
2 (Medium)	6 – 10	0.13	0.20	0.20	0.40	0.23±0.06
3 (Hard)	1 – 5	0.00	0.00	0.00	0.20	0.05±0.03

Compaction: P<0.001, GLIM, Poisson errors, logarithmic link function.

b) Field research on ABC oviposition site selection

An extensive evaluation of egg pod distribution was undertaken at 6 sites in SE Botswana. Fields and fieldside *Acacia* scrub were compared at each site, and soil samples from each sub-site were analysed. Findings from the field situation contrasted with the previous laboratory studies.

- **Acacia scrub is the preferred oviposition habitat under field conditions**

Statistical analysis, using GLIM, indicated that high egg pod density was not related to soil type but, rather, vegetation type was critical, and *Acacia* scrub was, on average, the preferred oviposition habitat irrespective of soil type. This was not consistent between sites however, as vegetation type, site and the interaction between these two factors all contributed significantly to the overall model (Table 1.7).

Table 1.7. Egg pod density under *Acacia* scrub and crop vegetation types at six sites.

Vegetation	Site						Mean
	Mmatseta	Letlhakane	Mmopane	Mogoditshane	Setshego	Kgaphamadi	
Acacia	54.4±2.7	24.9±3.7	34.1±1.9	45.7±4.7	52.9±5.6	82.0±15.1	49.0±5.0
Crop	59.2±6.0	48.8±11.3	37.2±4.2	34.1±1.5	38.5±3.3	38.8±4.4	42.0±3.0
Mean	56.3±2.7	36.9±7.5	35.7±2.2	41.4±3.8	44.1±4.8	61.1±11.6	

Significance of component effects: Vegetation: P = 0.02; Site: P <0.001; Interaction: P <0.001

- **Most egg pods are laid under bushes**

Examination of egg pod distribution beneath and around individual *Acacia* trees/bushes revealed that the number of egg pods was highest at 0.5m from the trunk, falling away significantly at greater distances (P<0.01)(Fig 1d).

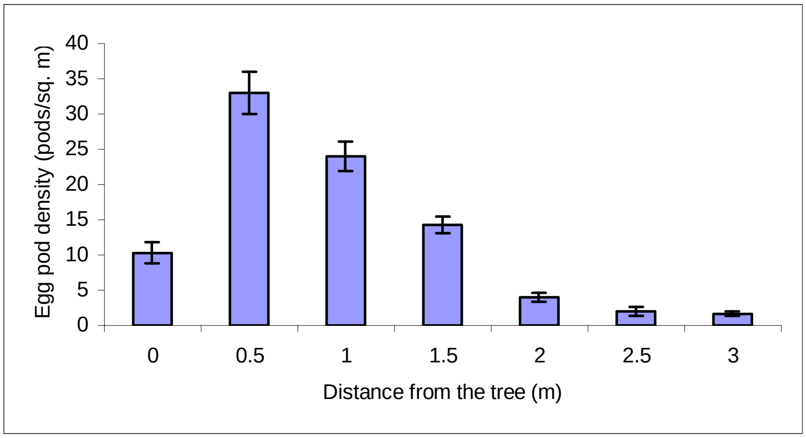


Fig. 1d. Density of egg pods sampled under *Acacia* tree.

Egg pods laid below the canopy of *Acacia* bushes experience a relatively stable environment compared to more exposed locations. They are sheltered all year round from exposure to strong radiant heat, and are also buffered from the cooling effects of cold winter nights. The soil in *Acacia* scrub areas is much more compacted than field soil, and hence less hospitable to the subterranean egg predator *D. helvolus* and there is a correspondingly lower level of egg mortality in fieldside scrub.

Summary of ABC population biology outputs (Outputs 1).

1.1 Egg diapause. Factors influencing diapause and egg hatching.

- Exposure to winter temperatures has no effect on % hatch, although prolonged low temperatures delay hatching.
- Soil saturation kills eggs.
- Incubation temperature affects rate of development and % hatch
- Soil moisture is essential only in the later stages of embryo development

1.2 Egg mortality. Field estimates of predation and egg parasitism.

- Annual egg mortality in SE Botswana is approximately 50%
- The major cause of egg mortality is predation by a subterranean ant.
- Egg parasitism is rare.
- Egg predation by ants is higher in crop fields than in *Acacia* scrub

Additional research : Oviposition

- Females avoid oviposition in very sandy soils
- Females prefer dry soil for oviposition
- Females prefer uncompacted soil for oviposition
- Acacia scrub is the preferred oviposition habitat under field conditions
- Most egg pods are laid under bushes

Outputs: 2 Forecasting Tool Development

2.1 Population model
2.2 Forecasting tool

Background
The fieldwork carried out on the ecology and population dynamics of ABC (see previous section) was directed towards improving our understanding of the factors that affect the cricket's development, survival and reproduction. The aim of the modelling work has been to utilise the new information obtained during the project to improve understanding of ABC population dynamics, and so provide better predictions of outbreak risk. Other important pests of semi-arid regions such as locusts, quelea and armyworm are migratory. This characteristic greatly complicates the task of predicting both the occurrence and location of outbreaks. ABC is flightless, and although highly mobile for a pedestrian insect, it probably does not move more than a few kilometres in its lifetime. As a result, ABC population dynamics can be modelled on the assumption that populations are continuous at a particular location and affected by the pertinent environmental and biotic variables at that location.

Armed with a forecast of outbreak risk for the next season, different stakeholders would have a basis on which to make preparations for ABC control. At different levels, this would involve budgeting for poison baits, making plans for trench digging, scouting in the scrub habitats adjacent to fields for early signs of ABC activity, and possibly even planning for cricket utilisation as poultry food.

The goal of the project's modelling work has been to develop a model that could explain the temporal pattern in the occurrence of ABC outbreaks, *i.e.* why outbreaks have occurred in some years and not others. Then, by starting to build up data on ABC abundance and rainfall for specific locations, it would be possible to test the model on a smaller scale and make predictions of outbreaks on this scale. In this project the modelling work is restricted to general patterns for regions of Botswana. Although historical rainfall data are available from a series of meteorological stations around the country, no systematic recording of ABC outbreaks has taken place.

Prior to the current project, the population dynamics of ABC were believed to be determined primarily by the rainfall conditions in the semi-arid environments where this cricket is found. Essentially it was thought that years with good rainfall would result in high levels of ABC egg hatch, good nymphal and adult survival, and high reproductive success, especially if preceded by a dry year. Conversely, years with poor rains were assumed to be poor years for crickets. Thus, it has been assumed that large populations of eggs remain in diapause in the soil until there is a year with good rains, when a large hatch occurs. The modelling work described here has shown that this paradigm is inadequate to explain ABC population dynamics.

Fieldwork during the course of this project has highlighted important causes of ABC mortality, which are likely to be most severe in years with good rains. Also as a result of project research, the pattern of rainfall during the course of the season is now also believed to be critical for ABC success and a lack, or a surplus, of rain at different times may have serious consequences for ABC mortality and reproduction.

Details of the model
The extent of quantification of the ecological relationships, which affect ABC population dynamics, varies greatly. Frequently, this understanding can be expressed as statements that certain conditions are better or worst than certain other conditions in their effects on aspects of ABC life history. Evidence from observations and experiments is not usually sufficiently complete to make confident quantitative estimates of the effects. In developing a forecasting model from the available data we therefore restrict the description of all model components to a three point ordinal scale: high, medium and low, this being sufficient to express concepts such as 'better', 'worse' and 'similar'.

Two kinds of relationships between model components are employed in the model. In the first, the value of a component is constrained by any one of a set of other components, and so the value is given by a relationship of the form $a = \text{Min}\{b,c\}$, meaning that the value of component a is determined by the smaller of the values of b and c. In the second type of relationship, any one of a set of components is sufficient to determine the value of the component concerned, and so the relationship has the form $a = \text{Max}\{b,c\}$ and the value of component a is determined by the larger of b and c. Naturally, the identity, high > medium > low holds throughout, and for computational convenience high, medium and low are coded 3, 2 and 1, respectively.

A qualitative description of rainfall
Directly or indirectly, much of the population dynamics of ABC is determined by the pattern of rainfall, both within and between seasons. In Botswana the rainy season occurs from October to April and the cold cloud duration (CCD) profile for that period can be used to provide an indication of both the pattern and amount of rainfall over the course of the season. Current CCD images were obtained from Meteosat and historical data from secondary data sources, notably, FAO/Artemis. Comparison of seasonal profiles of CCDs with their long-term average was used to highlight differences between seasons. These differences where summarised by making a distinction between the early, mid and late periods of the season (approximately, before mid December, mid December to mid February, and after mid February, respectively). Whether the rains were close to average, above average or below average, for each of the three periods is shown in Table 2.1 for southeastern Botswana for the period 1988 to 2002. Thus, each season is characterised by three parameters (early, mid, late) and each parameter can have one of three values (high, medium, low). This can be summarised using the following notation:

Season = {early, mid, late}, where (early, mid, late) = 1,2 or 3 (1)

For example, the year 2000 had wetter than average conditions in the early part of the season, a dry mid season and an average late season, so Season 2000 = {3,1,2}.

Biological reasoning and assumptions underlying the population model
Parameters determining the population dynamics of ABC are related to the seasonal rainfall pattern. The success of newly hatched ABC nymphs, and the later survival of older nymphs and adults, depends on continuity of food supply throughout the long life cycle. Failure of rains at any stage in the season will affect the proportion of hatching individuals that survive to reproduce successfully. Because survival is

constrained by periods of water and food stress, survival is related to the period in the season with the worst conditions, so

Nymph and adult survival = Min {early, mid, late} (2)

Fecundity is also constrained by sub-optimal rainfall conditions but it is assumed that it is the mid and late parts of the season that influence fecundity, and so

Fecundity = Min {mid, late} (3)

If high rainfall occurs in either the mid or late part of the season it was assumed that egg predation and/or waterlogging are increased, and therefore mortality would be higher. This leads to the expression,

Egg survival = 4 – Max {mid, late} (4)

To clarify with a numeric example, egg survival = 1 (low) if either mid or late = 3 (high). At the other extreme, egg survival = 3 (high) if neither mid nor late exceed 1 (low).

The contribution of each adult female to the egg bank is constrained both by her fecundity and by the subsequent survival of the eggs laid. If either is low, then the contribution to the egg bank is low and therefore,

Surviving eggs per adult = Min {fecundity, egg survival} (5)

Total egg recruitment to the egg bank can be high either because there are many adults or because reproductive success is high. This leads to the expression,

Total new eggs = Max {adults, surviving eggs per adult} (6)

Adult numbers are constrained either by poor conditions for survival during the season or by lack of eggs in the egg bank at the start of the season. This is expressed,

Adults = Min {total new eggs $_{\text{last season}}$, nymph and adult survival} (7)

This series of expressions (Equations 1 to 7) together define the model. One season is linked to the next by Equation 7 because the number of ABC emerging in a new season depends on the eggs previously accrued in the egg bank. Equations 1 to 7 are used to simulate ABC population dynamics over time.

Model predictions

Based on rainfall data (Table 2.1), the values of model components were determined for southeastern Botswana for the period 1988 to 2002 (Table 2.2). Because the model uses values from earlier years (eq. 7), in order to initiate the simulation, it was necessary to make an assumption about the total number of eggs in 1987. In fact, the model outcome proved not to be sensitive to this assumption.

The model predicted medium adult populations in three seasons: 1989/90, 98/99 and 99/00, and low populations in the others. We take a value of medium as an indication that an outbreak is more likely than when the value is low. In fact, it transpires that under the current assumptions of the model, only two adult states are possible, medium and low. This is because seasonal conditions favour either high fecundity or high egg survival but not both in the same season. As a consequence, the solution of equation 5 is always less than ‘high’. Should model assumptions be changed so that egg mortality constraints were relaxed in years of high fecundity, then it would be possible for the value of equation 5 to equal ‘high’.

It is important to note that the assumption of high egg mortality in high rainfall years is crucial to the performance of the model. In the initial phase of model development, no evidence of high egg mortality existed. A version of the model which assumed that both high fecundity and high egg survival were associated with high rainfall years failed to predict outbreaks correctly.

For an outbreak (*i.e.* the state, adults = medium) to be predicted, two factors must coincide: a large egg bank from the previous year and good nymph and adult survival in the current year. A large egg bank results when either a large numbers of adults are present, or when neither low fecundity nor low egg survival constrain egg production. As explained above, it is not possible for both fecundity and egg survival to be high, but it is possible for both to be medium. Thus, rainfall conditions most favourable to a large egg bank are those that give rise to medium values of these model components. Such conditions occurred in the seasons commencing in 88, 93, 97 and 98. The model gave raise to outbreak predictions in 89, 98 and 99 but not in 94. In 1994, nymph and adult survival was predicted to be low so although a good egg bank should have accrued in the previous year, the adult population in 1994 was not predicted to reach outbreak proportions.

Last season, 2001/2002 started with above average early rains in both southeastern and south central Botswana, the regions mainly affected by ABC outbreaks. Comparisons of the CCD profiles for 2001/2002 with the ten-year average show the higher than average cold cloud cover in the early part of the season (Figs. 2a, 2b). In the mid and later periods of the season, there was an interesting difference between the two regions. Southeastern Botswana had below average rainfall but south central had close to average. In the southeast where Season = {3,1,1} (see Equation 1), the lack of rains in the mid and late part of the season was expected to result in poor nymph and adult survival and low fecundity. Contribution to the egg bank was therefore predicted to be low, despite the fact that losses of newly laid eggs would also be expected to be low. In south central Botswana where Season = {3,2,2}, the contribution to the egg bank was predicted to be medium. The adult population that laid the eggs was, however, predicted to be low due to poor recruitment to the egg bank in the previous year. Thus no outbreak was expected.

In the next season, 2002/2003, outbreaks could occur in some areas. Where the current season followed the {3,1,1} pattern outbreaks should not occur because recruitment to the egg bank was too low. In areas where the current season followed a {3,2,2} pattern outbreaks are predicted if the 2002/2003 season has at least average rainfall in all three parts of the season, i.e. Season = {>1,>1,>1}.

Validation
Historical outbreak reports are limited but it is known that the model correctly predicts the general ABC situation over the last five years in southeast Botswana. Extensive outbreaks occurred in 98/99 and in 99/00 but they did not occur in 97/98, 00/01 or 01/02. Earlier reports are less reliable but many farmers in Makwate and Shoshong claimed there were outbreaks in 92/93 and 94/95, respectively (both places in southeastern Botswana). The model gives no suggestion that widespread outbreaks could have occurred in 92/93 with rainfall conditions predicted to impose constraints to the ABC population prior to and during that season. In 94/95, the rains were poor during both early and mid season so outbreaks were deemed unlikely. However, if pockets of average rain occurred then the egg bank from the previous season, 93/94, was predicted to be high enough to generate outbreaks in these pockets.

The current general nature of the predictions means that local variation is missed. For example, although ABC numbers did not reach outbreak proportions in 2001/2002, significant populations were found in certain areas.

The model does not consider the accumulation of eggs in the egg bank over more than one season, and in so doing it is assumed that the eggs laid in the previous year are the key determinant of the size of the egg bank. This may be reasonable, given that hatching and mortality take their toll on eggs accrued in previous years.

Judgements about whether the rains were close to average, above average or below average are currently made on a subjective basis. Some more objective protocol to compare each season with the long-term average is required for a more extensive implementation of the model. The CCD data used provided a summary for a large zone of southeastern Botswana. Spatially detailed outbreak prediction would require commensurate detail in the seasonal CCD profiles.

Conclusions
A model has been developed directly from the biological relationships which we now believe determine ABC population change. The model has correctly predicted the general outbreak status of ABC in Botswana over the last five years. Detailed spatial predictions were not attempted because of a lack of outbreak data to validate the model at this resolution. Now that we have a model that appears to work on a general scale, the possibility exists to start building up systematic records of ABC abundance from different locations.

The model incorporates an important new hypothesis about the factors that determine ABC success. The key issue is that a balance exists between fecundity and subsequent egg mortality. It is in the years when fecundity is moderate and mortality of the eggs not too great that the greatest contribution is made to the ABC egg bank. The consequence is that it is the years with ***average*** rains that are most likely to give rise to outbreaks in the following year (***if*** the conditions the following year also favour nymph and adult survival).

It is further possible that 'average' years are more favourable to the nymphs and adults than wetter years because of the greater levels of insolation and consequent higher temperatures. Field observations have shown that ABC tend to bask on the east side of *Acacia* bushes after dawn and on the west side in the late afternoon. It seems likely that the accumulation of sufficient 'heat units' will be an important determinant of fecundity as well as developmental rate.

Whilst the current project has revealed the possibility of high ABC egg mortality, more work is needed to establish whether the model is a good representation of reality in this respect. The possible deleterious effects of overcast conditions on ABC biology also need to be investigated. What is certainly true is that these assumptions about mortality (and/or fecundity) are essential to predict ABC outbreaks correctly. Without it, the model tends to predict outbreaks in the year ***after*** the high rainfall, rather, as is the case, during the high rainfall year.

ABC outbreaks do not appear to be the result of a mass hatching of eggs that have accumulated over a number of years. The model represents an alternative to this paradigm because it demonstrates than an accumulation of eggs in the *previous* season is an essential prerequisite to an outbreak in the current season. Although eggs are capable of surviving for at least three years in the soil, it may be that mortality takes too large a toll of these eggs for their effect to be very great. Rather than outbreaks occurring when a wet year follows a dry year, model predictions were consistent with data for the last five years in which outbreaks occurred when an *average* year was followed by a wet year (1999) or a second average year (1998).

Summary of ABC forecasting tool development outputs (Outputs 2).

- Using new ecological insights, a population model was developed which correctly predicted widespread ABC outbreaks in Botswana over the past 5 years.
- The previous assumption that a large 'egg bank' could remain in the soil in diapause through dry years, until optimal hatching conditions occurred now appears very unlikely on ecological grounds and this paradigm does not adequately explain the observed pattern of ABC outbreaks
- A key element of the model is the existence of a balance between adult fecundity and egg mortality – that high fecundity and low egg mortality do not occur in the same season. Consequently, years with average rains are most likely to generate an outbreak in the following year, provided the pattern of rainfall then favours nymphal/adult survival.

Table 2.1. Summary of rainfall in southeastern Botswana for the last 13 seasons (October to April). Rainfall: less than average (1), near average (2), more than average (3).

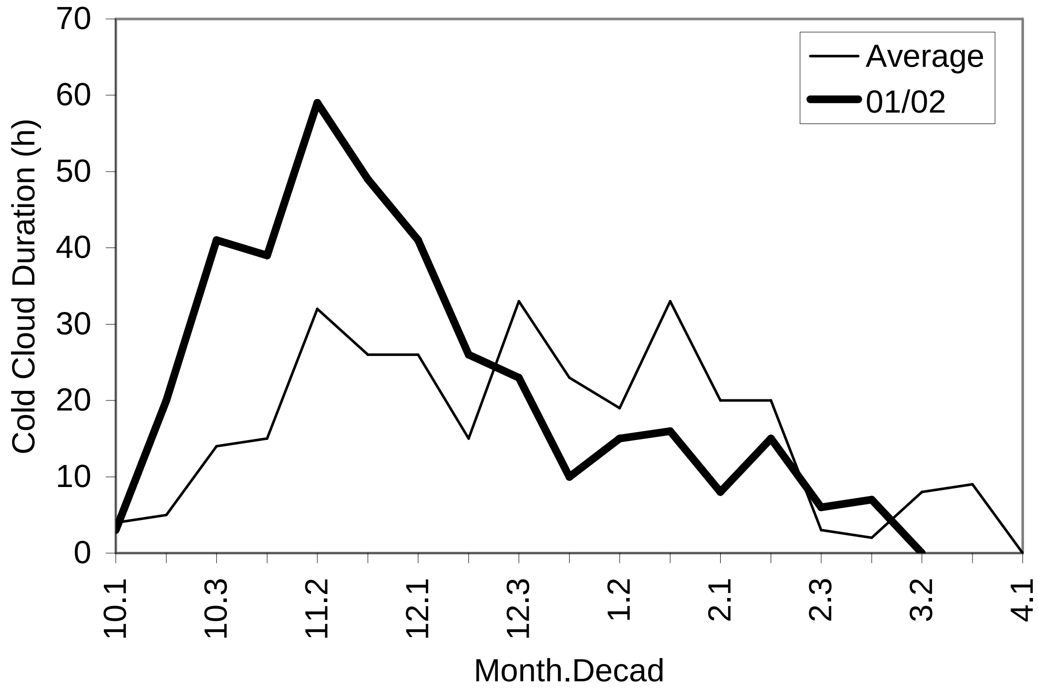
Season beginning	Period in season early	mid	Late
1988	1	2	2
1989	2	3	3
1990	1	3	3
1991	1	1	1
1992	3	1	1
1993	1	2	2
1994	1	1	2
1995	3	3	3
1996	3	3	3
1997	3	2	2
1998	3	2	2
1999	3	3	3
2000	3	1	2
2001	3	1	1

Table 2.2. Model predictions for the period 1988/89 to 2002/03. High (3), medium (2) and low (1) values are indicated for each model component. The model can be interpreted as predicting outbreaks in the seasons starting in 1989, 98 and 99 when Adults = 2 (see text for explanation).

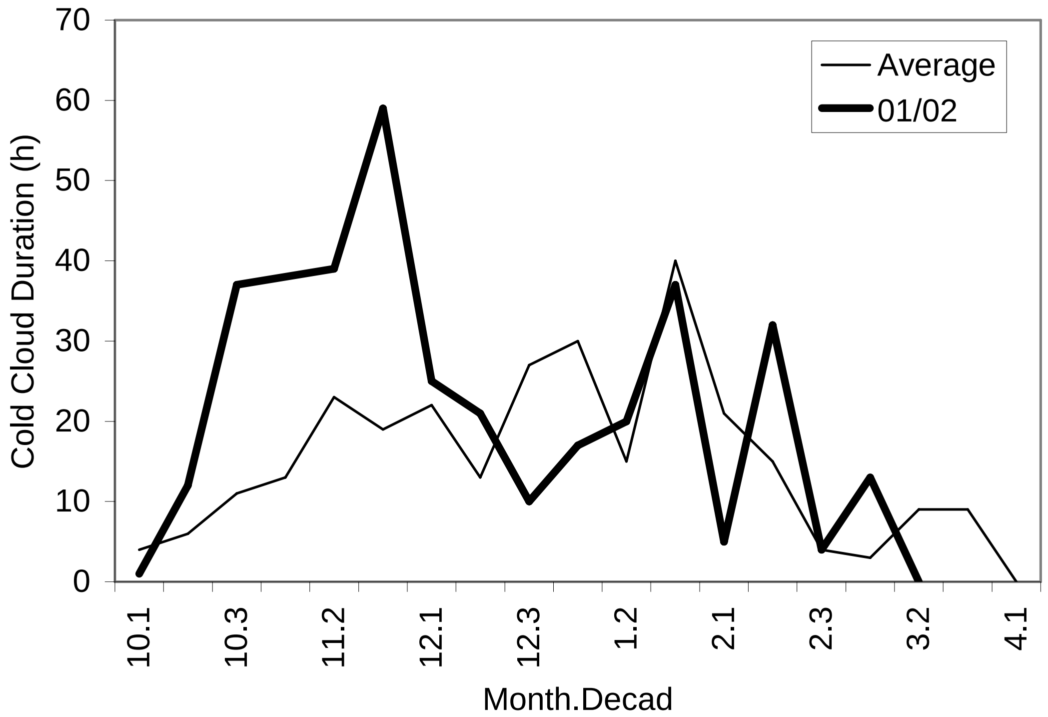
Season beginning	Nymph and adult survival	Fecundity	Egg survival	Surviving eggs per adult	Total eggs	Adults
					1	
1988	1	2	2	2	2	1
1989	2	3	1	1	2	**2**
1990	1	3	1	1	1	1
1991	1	1	3	1	1	1
1992	1	1	3	1	1	1
1993	1	2	2	2	2	1
1994	1	1	2	1	1	1
1995	3	3	1	1	1	1
1996	3	3	1	1	1	1
1997	2	2	2	2	2	1
1998	2	2	2	2	2	**2**
1999	3	3	1	1	2	**2**
2000	1	1	2	1	1	1
2001	1	1	3	1	1	1

Figures 2a, 2b. Comparison of Cold Cloud Durations for 2001/2002 with the ten-year average for two regions of Botswana a) southeast, b) south central

a.



b.



Outputs: 3. Investigations into the chemical ecology of Armoured Bush Crickets.

3.1 Plant semiochemicals and ABC attraction
3.2 Cricket-derived chemical attractants
3.3 Chemical analysis

Background.
Insects utilise chemical cues in a variety of ways to guide their behaviour, *e.g*. in relation to feeding or finding a mate or oviposition site. The tactical deployment of volatile chemicals identified as semiochemicals has been used successfully to manipulate the behaviour of many insect pests, luring them into traps or disrupting their natural mate-finding behaviour (Ridgway *et al*. 1990). As well as being effective, control using semiochemicals has the additional advantage of being environmentally benign. This section investigates whether semiochemicals could be used to manipulate the behaviour of armoured bush-crickets (ABC) and thereby contribute to managing this damaging pest.

With the exception of locusts, which have been studied extensively, little is known about the role of semiochemicals in the chemical ecology of Orthoptera. There is extensive evidence that bush-cricket mate location is mediated by acoustic and vibrational cues - this is well documented across the Tettigoniidae (Gwynne 2001). The mating behaviour of *Acanthoplus,* described by Power (1958) for *A. discoidalis* (syn. *A. bechuanus*) and by Mbata (1992) for *A. speiseri,* conforms to this norm. But although it is unlikely that semiochemicals are involved in long range mate-location, they might function at close range. Chemical stimuli have been shown to play a role in mate recognition in certain other ensiferans, namely cuticular hydrocarbons in the cricket *Gryllus bimaculatus* (Tregenza & Weddell 1997), and faecal volatiles in the king cricket *Libanasidus vittatus* (Bateman & Toms 1998).

ABC forage actively and feed on a wide variety of foods, including grasses and cereal panicles, whilst they also scavenge opportunistically on carrion and even on injured crickets. Field observations suggest that ABC locate food items accurately within structurally complex microhabitats, and they do so particularly quickly if they are starved prior to release. Movements of the elongated antennae and palps when in the vicinity of food also suggest that ABC detect food odours. So the real significance of semiochemicals for ABC is probably in the context of food location and most of the work in the present section has concentrated on this aspect.

Insecticidal baits have been deployed previously, with limited success, against ABC in northern Namibia (Wohlleber 1996, 2000). The present project has refined bait application further with the development of the baited trench as a control technique. But whatever the method of presentation, the effectiveness of a bait will depend on how attractive it is to ABC, and so the focus of the following section is on determining substances that are attractive to ABC by bioassay and identifying the volatile components present in known food items.

Behavioural Studies

ABC availability

Laboratory-based behavioural studies outside Botswana were constrained by an unreliable supply of ABC for experimental work. Other than in the first year (2000), few ABC could be collected in the wild owing to population recession and importation from Botswana was problematic because of strict cross-border controls. Laboratory rearing of ABC, as discussed in Outputs 1, proved more difficult than anticipated. In particular the synchronised massed hatch needed to produce a substantial cohort of ABC for larger behavioural trials was never achieved. Having said this, significant advances were made using those insects that were available.

3.1 Bioassays with plant material and plant-derived substances

Plant-derived substances tested by bioassay included potential baits (food), plant materials and chemical compounds identified from the preferred host, sorghum.

Y-tube bioassays (2000)

Bioassays were conducted at GCI-Potchefstroom, using various known ABC foods, including maize and sorghum, that could potentially be used as baits in cricket control. First and final reaction (after three minutes) was scored in these bioassays. A total number of 770 crickets were used and 2310 minutes of observations made.

ABC reaction to the stimuli presented in the rather confined Y-tube olfactometer did not reach formal significance in any individual case (Table 3.1). However, a number of baits and compounds elicited positive reaction at the $p<0.07$ level, suggesting there was attraction. Foodstuffs that were judged to have elicited positive responses were: oats, maize meal mixed with fishmeal, and coarse sorghum chaff (all $p<0.07$). Although there was also a tendency to select very coarse sorghum chaff, no significant difference in selection was found comparing sorghum chaff and maize meal, two of the main candidates as bait ingredients, in a two-choice test in the Y-tube (Table 3.1).

Chemical compounds, associated with volatiles produced by sorghum panicles, that were observed to elicit a positive reaction by ABC in the Y-tube were 2-phenylethanol and benzyl alcohol (Table 3.2).

Wind-tunnel bioassays (2002)

Bioassays were also conducted under less confined conditions in a wind tunnel, 1.2m x 0.4m x 0.4m with a near-laminar airflow of 0.3m s^{-1}, using plant-derived substances all of which, except (*E*)-β-farnesene, had been identified as volatile components of sorghum panicles (described in the following section). Compounds, in hexane, were applied to filter paper discs (7cm diameter), up-wind from the cricket release point. A similar filter paper disc was placed at the opposite end of the tunnel to eliminate bias due to any potential visual stimuli. Crickets were put in a shallow petri dish and placed at the release point in the centre on the wind tunnel. Their behaviour was then monitored for 15 minutes. The temperature inside the wind tunnel ranged between 25°C and 29°C. A total number of 225 crickets were used and 3375 minutes of observations made.

Cricket behaviour was scored as follows:

1st reaction: the direction the cricket turned after placing the petri dish into the tunnel.
2nd reaction: the final position in the tunnel where the cricket was observed after 15 minutes.

In nearly all cases the 1st reaction was in the same direction from the centre as the final position. Results are provided in Table 3.3. To summarise, the presence of a fresh sorghum panicle (variety *Macia*) elicited a strong positive response from crickets, both in 1st and 2nd reactions. Compounds that elicited a weaker positive response in both 1st and 2nd reactions were decanal and 4-ethylacetophenone. Benzyl alcohol (10 mg/ml) and nonanal (10 mg/ml) elicited positive 2nd reactions.

3.2 Bioassays with cricket derived substances:

Dead crickets

Because crickets are observed to be cannibalistic and appear to aggregate quickly around dead or dying crickets it was suspected that there might be a chemical cue originating from dying crickets that could be used as attractant.

Y-tube bioassays (glass Y-tube) were performed using recently killed ABC individuals as the target. No positive response was observed when crickets had to choose between the blank arm and the arm baited with a dead ABC (40 replicates) (Table 3.4).

Oviposition bioassays

Female ABC tend to oviposit in shade, often below *Acacia* bushes, where egg pods are frequently aggregated. Whether this amounts to passive aggregation due to a common need for shade, or active, chemically-mediated aggregation as found in certain locust species, is not known. Hence a study was undertaken to assess attraction of gravid females towards fresh egg pods, conducted in a large Y-tube apparatus constructed of wood (base arm 50 cm, Y-arms 50 cm in length).

a. Y-tube bioassay with egg pods

Six evaluations were conducted with egg pods in Y-tube bioassays (20 replicates). Egg pods of different ages were put in the baited arm. No significant attraction towards the egg pod-baited arm could be detected (Table 3.1).

b. Evaluation of aggregation behaviour during oviposition

Laboratory experiments were conducted to determine whether females exhibit aggregation behaviour when they oviposit. Methods used in this bioassay were similar to those used by Saini *et al*. (1995) for evaluation of semiochemicals of locusts. Female crickets were placed in cages with false floors in which two containers of sand were placed. Females therefore could not oviposit anywhere other than in the sunken containers of sand. One container (7 cm diameter) was baited with egg pods laid during the day and previous night while the other contained only sand. No significant difference was observed between the numbers of egg pods laid in the baited and unbaited containers. This experiment was replicated three times.

Since no significant attraction was observed towards soil baited with egg pods or to ovipositing females, it appears unlikely that cricket-derived chemical cues play a role in oviposition site selection. On one occasion, however, what appeared to be aggressive behaviour was observed at the furthest end of the Y-tube, when a test female made vigorous attempts to insert her ovipositor through the wire mesh separating her from an ovipositing target female. This raises the possibility that oviposition aggregation might be mediated by visual cues. Another interpretation is that the test female was attempting to drive the ovipositing female away and steal her oviposition hole, since such holes are probably costly to dig in hard dry soils (in terms of energy, time and risk exposure).

3.3 Chemical analysis

Isolation of volatiles from flowering and soft dough stage sorghum panicles.
Air entrainments of the volatiles from the sorghum cultivars *Seredo* and *Marcia* were performed in the field at GCI Potchefstroom and under glasshouse conditions at Rothamsted Research. Subsequent chemical analysis took place at Rothamsted.

Entrainment of volatiles was performed on growing plants, using portable equipment recently developed at Rothamsted. The sorghum panicle was enclosed in a customised open-bottomed glass vessel (100mm dia. x 300mm length) and the bottom was closed with two semicircular aluminium plates that fitted loosely around the stem. Any large gaps between the plates and the stem were packed with silanised and baked glass wool. Air, purified by passage through an activated charcoal filter, was pumped up through the vessel through a port in one of the aluminium plates and volatiles were then collected on Porapak or Tenax absorbent tubes in collection ports at the top of the vessel. Air was also drawn out through the collection tubes by further pumps. By controlling the flow rates so that more clean air was pumped in than was drawn out, the risk that unfiltered air would be drawn into the vessel from outside was avoided, whilst obviating the need for an injurious tight seal around the stem. Typical flow rates used were 1000ml/min in and 700ml/min out. All connections were made using PTFE tubing and ferrules and as much as possible of the equipment, especially the glassware, was heated at 180°C for at least 2 hours before use. Porapak tubes were conditioned at 140°C with filtered nitrogen pumped through for 2 or more hours and Tenax tubes were conditioned similarly but at 220°C.

Analysis of volatiles was by gas chromatography (GC), using both polar and non-polar phases, and GC-mass spectrometry (GC-MS). The collected volatiles were eluted from the Porapak tubes with freshly distilled diethyl ether and analysed by conventional injection of the solution into the GC inlet whereas volatiles collected on Tenax tubes were transferred directly onto the GC column by thermal desorption using the OPTIC system. In the latter case everything collected was analysed at once while replicate analyses were possible from the Porapak entrainments allowing confirmation of GC-MS tentative identifications by GC co-injection with authentic samples. However, collection times with Porapak generally needed to be considerably longer.

At Rothamsted, experiments were carried out to collect volatiles at flowering and soft dough stages, taking samples on a daily or periodic basis. Experiments were replicated four times. Figure 3a shows some typical chromatograms from one such experiment in which volatiles were entrained for 24h periods (except for the last which was 96h). At GCI Potchefstroom, in addition to the normal collection of volatiles from sorghum panicles, repeat entrainments of individual panicles were done during photophase and scotophase to investigate the diel periodicity of volatile production.

Overall there was a good correlation between volatile profiles from both cultivars of sorghum grown in South Africa and the UK, although there were some differences in the proportions of individual components. In particular, aromatic compounds dominated the volatile profiles obtained from sorghum grown in the field in South Africa (Figure 3b).

During the course of this project a total of 45 volatile compounds were identified from the panicles of sorghum cultivars. These are all listed below (in alphabetical order) and as can be seen they largely comprise ubiquitous plant or flower volatiles:-

Acetophenone
Anisole*
Benzaldehyde*
Benzyl alcohol*
trans-Caryophyllene*
1,8-Cineole
Decanal*
1,3-Diacetylbenzene
1,4-Diacetylbenzene
1,2-Dimethylbenzene
1,3-Dimethylbenzene
1,4-Dimethylbenzene
4,8-Dimethyl-1,3,7-
-nonatriene*
2-Ethylacetophenone
4-Ethylacetophenone*
2-Ethylbenzaldehyde
4-Ethylbenzaldehyde*
Ethylbenzene
(*E*,*E*)-α-Farnesene
Heptanal
Hexanal
(*Z*)-3-Hexen-1-yl acetate
Indole*
4-Isopropylbenzyl alcohol
Limonene
Linalool*
Linalool oxides (furans)
6-Methyl-5-hepten-2-
-one*
2-Methyl-4-pentanal
Methyl salicylate*
Myrcene
Nonanal*
(*E*)-Ocimene
Octanal*
1-Octen-3-ol
Phenol
Phenylacetaldehyde*
2-Phenylethanol*
α-Pinene
β-Pinene
Propylbenzene
Sabinene
Toluene
4,8,12-Trimethyl-
-1,3,7,11-tridecatetraene
Undecanal

The failure to obtain a supply of crickets in UK meant that they were not available for coupled GC-electroantennography (GC-EAG) studies, which would have identified compounds in the GC analysis that produce an electrophysiological response in the insect. As an alternative approach, compounds (marked with * in the above list) were provided for wind tunnel studies based on their differential appearance in the volatile profiles of flowering and soft dough stages. As mentioned above, this approach yielded a number of compounds eliciting behavioural activity in ABC although attraction is likely to be mediated by a complex of volatiles. Lack of insects did not allow studies with mixtures to be done.

Volatile profiles from flowering and soft dough stages contained many compounds in common, which is to be expected since by the time the panicle is in the last stages of flowering some grains are at the soft dough stage. It is therefore likely that relative amounts or ratios of compounds will be important in determining host location of the preferred soft dough stage by armoured bush crickets. The rapid rise and subsequent fall in the level of 2-phenylethanol as flowering progresses, suggests that this compound is chiefly associated with the flowering phase (Figure 3a). The peaks labelled 5 and 6 are not present in the early flowering volatile profiles but appear as major components in the soft dough entrainments, suggesting that these compounds, identified by GC-MS as two octadienone isomers, are associated with the post-flowering stage. The octadienones (*E*,*E*)- and (*E*,*Z*)-3,5-octadien-2-

one have previously been shown, by GC-EAG, to have electrophysiological activity in the desert locust, *Schistocerca gregaria*, (Torto *et al*. 1999) and in corn rootworms, *Diabrotica* spp. (Cosse & Baker, 1999). In the desert locust these compounds have been shown to form part of the releaser pheromone system that mediates group oviposition and as the principal primer signal responsible for maternal transfer of gregarious character. Thus in the desert locust these compounds have dual releaser and primer roles (Malual *et al*., 2001). Since these compounds are not commercially available, they are being synthesised in order to confirm the GC-MS identifications and provide material for bioassay.

Other compounds which show a significant quantitative variation over the course of the experiments are nonanal and decanal, two of the major peaks at Day 1 (0–20% flowering) but much reduced as a proportion of the total even by Day 4 (60-80% flowering). In other experiments benzaldehyde, benzyl alcohol and indole were identified as minor peaks, in addition to those compounds shown in Figure 3a.

Overall levels of volatiles emitted by flowering sorghum panicles were surprisingly low throughout, with a maximum production in any experiment of 235 $ng.h^{-1}$. This can be compared with c. 900 $ng.h^{-1}$ total volatiles from a flowering wheat panicle (Bruce 2002, unpublished) and 450-1125 $ng.h^{-1}$ for a single raceme of oilseed rape (Agelopoulos *et al*. 2001, unpublished). Even these figures are small compared with the reported 170 $\mu g.h^{-1}$ emitted by a single flower of the orchid *Epidendrum ciliare* (Kaiser 1997).

There is significant diel periodicity in the production of volatiles (Table 3.5). All through panicle development larger amounts of volatiles were produced during photophase than during scotophase. The estimated total amount of volatiles collected in the scotophase at 100% flowering was 69 $ng.h^{-1}$ whilst in the following photophase entrainment the figure was 192 $ng.h^{-1}$. Figures for photophase and scotophase when flowering had finished were 167 and 30 $ng.h^{-1}$ respectively. Given that 50% flowering produced 235 $ng.h^{-1}$ of total daytime volatiles there seems to be a relatively gradual decline in production as flowering progresses through to soft dough stage. Amounts of individual compounds as a proportion of total volatiles production can be very different between night and day (Table 3.6). The proportion of 2-phenylethanol present in the scotophase entrainments is higher, especially in the later stages of panicle development, than during the photophase. Phenylacetaldehyde shows the opposite trend.

Entrainment of volatiles from other host plants (2001, Potchefstroom)
Panicles of millet, *Pennisetum glaucum*, cv. Okashana-1, were entrained at 50% and 100% flowering, on several plants growing in the field in South Africa. Despite difficulties in analysis arising from the high humidity in the field during the period when these entrainments were conducted, it was possible to make tentative identifications of benzyl alcohol, (*E*)-ocimene, 2-phenylethanol and indole and confirm the presence of 6-methyl-5-hepten-2-one and (*Z*)-3-hexen-1-yl acetate by co-injection. The absence of benzaldehyde and α-pinene were also confirmed by co-injection. Of particular interest was the presence in the later flowering stage of peaks with corresponding Retention Indices to those of the two isomers of octadienone that were identified as present in comparable sorghum entrainments.

The flower panicles of wild sorghum were entrained in the field and analysis was able to confirm the presence of phenylacetaldehyde and the absence of benzyl alcohol in the samples although total levels of volatiles collected in the area were very high, even in the blank entrainment.

Wild *Urochloa* grass, a preferred food plant, including flowering panicles, was entrained. However, the low levels of volatiles in the samples have so far precluded identification.

Entrainment of volatiles from crickets (2001, Potchefstroom)
Armoured bush crickets were entrained in 90mm x 200mm vessels which were half filled with washed and baked sand, some also contained a dead acacia twig as support for the crickets. In all cases the appropriate blank entrainments were run. Two entrainments of males, a large number of entrainments of females, mostly thought to be gravid although only in two cases were egg pods found, and two of females with a spermatophore were done. Analysis of the samples consistently showed the presence of the normal alkanes, nonane through to heptadecane, with considerable variation in relative amounts (thus ruling out the possibility of contamination), the most abundant being tetradecane (mean of seven entrainments - 5.6% of total volatiles) and hexadecane (mean - 2.5%). All of the compounds were present in virtually all of the samples with no significant differences between the various groups of crickets entrained suggesting little or no sexual diamorphism in the production of these compounds. As referred to at the beginning, some longer chain hydrocarbons have been implicated in mate recognition in field crickets. There are many other reports in the literature of long chain hydrocarbons being implicated in insect recognition and as sex pheromone components. Often those studies would not have detected the lower alkanes found in the present work as they involved evaporation steps during which such volatile compounds would be lost. Some of the lower *n*-alkanes (C11 – C18), however, have been found to affect the behaviour of insects in other ways such as in alarm pheromones and overcrowding factors (see Howard and Blomquist 1982 for a review of this subject).

Conclusions

Despite the difficulty in obtaining a good supply of insects each year, which has had a considerable impact on the project’s ability to conduct electrophysiological and behavioural studies, considerable progress has been made in understanding the chemical ecology of ABC. In particular it has been clearly demonstrated that *A. discoidalis* is attracted to volatiles from sorghum panicles and less clearly to baits made from other cereals. In contrast, no attraction could be demonstrated toward freshly killed ABC, nor was there any evidence of gravid females being attracted towards freshly laid egg pods.

The volatile compounds produced by sorghum panicles in particular were subjected to detailed chemical analysis. While the overall levels of volatiles produced were surprisingly low a number of compounds were identified that are of interest for further studies. In addition to the individual compounds showing activity, the octadienones that were identified in the volatiles collected from the later stages of sorghum panicle development and from millet panicles are of special interest since they are known to show physiological activity in other insects, including the desert locust. Behavioural and electrophysiological studies with these compounds should be a priority for future studies. Several of the other compounds found in sorghum flower volatiles were shown to be active in behavioural studies. These included 2-phenylethanol and benzyl alcohol. It is worth noting that these and other aromatic compounds formed a higher proportion of the sorghum volatiles collected in the field in South Africa than in the glasshouse in UK. In South Africa entrainments demonstrated that the production of volatiles by sorghum panicles shows diel periodicity, higher levels being emitted in the photophase.

Benzyl alcohol was identified as a component of the volatiles collected from two female crickets, which is of interest as this compound is also found in the volatiles of sorghum panicles and was shown to be attractive in behavioural studies. Entrainments of volatiles from ABC have also shown the presence of a number of lower n-alkanes (C9 –C17) in varying proportions. Although there does not seem to be any correlation with gender or reproductive activity there remains the possibility that these compounds may have a role in conspecific or mate discrimination, acting in concert with the known acoustic communication system.

Table 3.1. Y-tube olfactometer results with ABC derived substances.

		First reaction				Final reaction			
Treatment	**n**	**Baited arm**	**Unbaited arm**	**No reaction**	**Sign level**	**Baited arm**	**Unbaited arm**	**No reaction**	**Sign level**
Dead ABC *vs* dry blank (high air flow rate)	20	6	3	11	NS	9	4	7	NS
Dead ABC *vs* dry blank (low air flow rate)	20	10	9	1	NS	10	9	1	NS
Fresh Egg pods(4) in sand *v*s sand blank (09:00-10:00)	10	3	0	7	NS	3	1	6	NS
Day old egg pods (6) *vs* sand blank (08:00-10:00)	26	9	10	7	NS	10	13	3	NS
Fresh loose eggs (20) *vs* sand blank (14:30-16:00)	16	7	6	3	NS	6	7	3	NS
Fresh pods (14hrs) *vs* sand blank (09:00-11:00)	20	10	10	0	NS	10	10	0	NS
Fresh pods (14hrs) *vs* sand blank (09:00-11:00)	20	13	7	0	NS	13	7	0	NS
Pods (20hrs)(same pods as above) *vs* sand blank (16:00-18:00)	20	6	13	1	NS	5	10	5	NS

Table 3.2. Y-tube olfactometer results with potential baits for use in control of Armoured Bush Cricket (May 2000).

		First reaction				Final reaction			
Treatment	**N**	**Baited arm**	**Unbaited arm**	**No reaction**	**Signif level**	**Baited arm**	**Unbaited arm**	**No reaction**	**Sign level**
Wet maize meal *vs* dry blank	20	7	7	6	NS	8	6	6	NS
Wet maize meal *vs* wet blank	20	8	12	0	NS	10	10	0	NS
Maize meal+fish meal *vs* wet blank	8	4	4	0	NS	5	3	0	NS
Maize meal+fish meal *vs* dry blank	20	7	5	8	NS	14	6	0	0.07
Wet fish meal *vs* dry blank	20	10	9	1	NS	10	9	1	NS
Wet fish meal *vs* wet blank	40	20	19	1	NS	19	19	1	NS
Very coarse sorghum chaff *vs* wet blank	20	14	6	0	0.073	14	6	0	0.07
Less coarse sorghum chaff *vs* wet blank	20	11	7	2	NS	13	6	1	NS
Sorghum flower *vs* wet blank	20	10	6	3	0.317	9	8	2	NS
Maize silk *vs* wet blank	20	9	9	2	NS	7	11	2	NS
Sorghum ear *vs* wet blank	20	6	9	5	NS	7	9	4	NS
Oats *vs* wet blank	20	13	5	2	0.059	14	3	3	NS
Maize meal *vs* Very coarse sorghum	20	8M:10S			NS	4M:9S			NS
BLANK *VS* BLANK	20	8	12	0	NS	8	12	0	NS

Table 3.3 Y-tube olfactometer results with plant derived substances (May 2002).

		First reaction				Final reaction			
Treatment	n	Baited arm	Unbaited arm	No reaction	Sign level	Baited arm	Unbaited arm	No reaction	Sign level
Thomac lure *vs* dry blank	20	9	8	3	NS	5	10	5	NS
2-phenyl-ethanol *vs* dry blank (low flow)	20	9	10	1	NS	11	9	1	NS
Phenyl acetaldehyde *vs* dry blank (lowflow)	20	10	7	3	NS	10	8	2	NS
Benzyl alcohol *vs* dry blank (low flow)	20	8	11	1	NS	6	13	1	0.108
Linalool *vs* dry blank (low air flow)	20	10	7	3	NS	10	7	3	NS
2-phenyl-ethanol *vs* dry blank (high flow)	20	12	4	4	0.045	8	6	6	NS
Phenyl acetaldehyde *vs* dry blank (highflow)	20	7	6	7	NS	9	9	2	NS
Benzyl alcohol *vs* dry blank (high flow)	20	12	2	6	0.015	11	4	5	0.070
Linalool *vs* dry blank (high air flow)	20	3	4	13	NS	5	9	6	NS
Nonanal (slow release capsule)	20	7	12	1		6	12	2	
Nonanal (cotton bud high release)	10	4	5	1		4	5	1	
Decanal (slow release capsule)	20	10	10	0		11	9	0	
Decanal (cotton bud high release)	10	5	1	4		5	2	3	
Acetophenone (slow release capsule)	20	5	10	5		6	12	2	
Acetophenone (cotton bud high release)	10	2	7	1		2	6	2	
4-ethylacetophenone (slow release capsule)	20	8	9	3		7	10	3	
4-ethylacetophenone (cotton bud high release)	10	5	3	1		3	4	3	
6-methyl-5-hepten-2-one (slow release capsule)	20	11	9	0		10	9	1	
6-methyl-5-hepten-2-one (cotton bud high release)	10	2	7	1		2	7	1	

Table 3.4. Effect of different compounds on ABC behaviour in a wind tunnel.

COMPOUND	CONCENTRATION (mg/ml)	No of ABC	1ST REACTION positive	1ST REACTION negative	1ST REACTION neutral	FINAL REACTION positive	FINAL REACTION negative	FINAL REACTION neutral
Blank	-	15	4	0	10	2	3	6
Macia panicle	-	10	7	0	2	6	1	1
Benzyl alcohol	10	5	1	2	2	5	0	0
Benzyl alcohol	1	4	3	1	0	3	1	0
Benzyl alcohol	0.1	4	0	2	1	0	2	0
Decanal	10	5	3	0	0	2	0	1
Decanal	1	4	0	2	2	0	1	3
Nonanal	10	6	0	2	4	6	0	0
Nonanal	1	4	2	1	0	2	1	0
Nonanal	0.1	4	2	1	0	1	0	2
Benzaldehyde	10	5	2	0	3	4	1	0
Benzaldehyde	1	4	1	1	1	3	0	0
Benzaldehyde	0.1	4	1	0	2	1	1	1
Indole	10	5	1	0	4	1	3	1
Indole	1	4	1	2	1	3	1	0
(E) - B - Farnasene	10	5	2	0	2	1	1	2
(E) - B - Farnasene	1	4	0	3	1	1	2	1
(E) - B - Farnasene	0.1	4	0	2	0	0	2	0
Anisole	10	5	0	0	3	1	1	2
Anisole	1	4	2	0	2	2	1	1
2 Phenyl etanol	10	5	2	0	0	1	0	2
2 Phenyl etanol	1	4	0	2	2	2	1	1
2 Phenyl etanol	0.1	4	0	1	2	1	2	0
Octanal	10	5	1	2	2	3	2	0
Octanal	1	4	0	1	2	1	1	1
4-Ethylbenzaldehyde	10	5	0	1	4	1	1	4
4-Ethylbenzaldehyde	1	5	0	0	5	3	0	2
Phenylacetaldehyde	10	5	1	1	1	0	2	2
Phenylacetaldehyde	1	4	0	1	2	0	1	2
Dimethyl nonatriene	10	5	1	0	3	3	1	0
Dimethyl nonatriene	1	4	2	0	1	2	0	1
Dimethyl nonatriene	0.1	4	2	1	1	1	2	1
Linalool	10	5	1	3	1	1	1	3
Linalool	1	4	1	0	1	1	0	1
6-Methyl-5-Hepten-2-one	10	5	0	1	4	2	1	2
6-Methyl-5-Hepten-2-one	1	4	2	1	1	1	2	1
	0.1	4	0	1	3	1	3	0
Methyl salicylate	10	5	1	1	3	1	1	3
Methyl salicylate	1	4	0	1	3	1	1	2
Methyl salicylate	0.1	4	0	2	1	1	3	0
4-Ethylacetophenone	10	5	3	0	2	4	0	1
4-Ethylacetophenone	1	4	0	0	4	1	1	2
1-Octanol	10	5	3	1	1	4	1	0
1-Octanol	1	4	1	0	3	0	1	3
Trans-caryophylene	10	5	1	1	0	1	1	0
Trans-caryophylene	1	4	1	0	3	3	0	1
Trans-caryophylene	0.1	4	0	1	3	1	3	0

Table 3.5. Entrainment of volatiles from sorghum flower & soft dough stage heads.

Compound	Approximate amount collected (ng.h^{-1})							
	Plant A				Plant B			
	A1	A2	A3	A4	B1	B2	B3	B4
benzaldehyde	1.7	0.7	2.5	0.7	4.3	0.9	4.0	1.1
benzyl alcohol	-	0.7	1.6	-	-	0.7	1.9	0.5
phenylacetaldehyde	1.3	0.5	22.2	1.5	11.9	3.1	11.5	3.7
nonanal	5.4	1.3	4.4	2.1	16.5	6.8	24.2	1.9
2-phenylethanol	4.7	0.9	11.9	7.4	26.2	11.6	28.4	19.7
methyl salicylate	1.7	0.4	4.7	1.5	7.1	1.6	12.7	1.6
decanal	3.7	1.5	3.7	1.0	15.3	3.4	6.8	1.5
(E)-caryophyllene	1.5	0.4	-	-	7.4	1.0	2.1	0.8

Shaded columns represent entrainments conducted during scotophase. A1 and B1 – approximately 50% flowering, A2, B2 and B3 – approximately 100% flowering, A3, A4 and B4 – finished flowering

Table 3.6 Proportion of individual compounds (mean data from 3 experiments).

Compound	Amount collected as % of total volatiles				
	50% flowering,	100% flowering	100% flowering	Flowering over	Flowering over
benzaldehyde	2.3	2.1	1.7	1.5	2.2
benzyl alcohol	-	1.0	1.5	1.0	0.6
phenylacetaldehyde	4.3	6.0	4.4	13.3	6.6
nonanal	8.3	12.6	9.8	2.6	5.1
2-phenylethanol	10.6	14.8	15.4	7.1	34.0
methyl salicylate	3.1	6.6	2.3	2.8	4.0
decanal	6.8	3.5	5.5	2.2	3.3
(E)-caryophyllene	3.1	1.1	1.6	-	1.0

Shaded columns represent entrainments conducted during scotophase

Figure 3a. Gas chromatograms (by thermal desorption onto an HP-1 column) of some of a series of daily entrainments of volatiles from a sorghum flower head.

Numbered peaks correspond to the following compounds:- 1 = 6-methyl-5-hepten-2-one, 2 = sabinene, 3 = myrcene, 4 = phenylacetaldehyde, 5 = octadienone (isomer a), 6 = octadienone (isomer b), 7 = nonanal, 8 = 2-phenylethanol, 9 = 4,8-dimethyl-1,3,7-nonatriene, 10 = decanal, 11 = caryophyllene
x = unknown, y = unknown

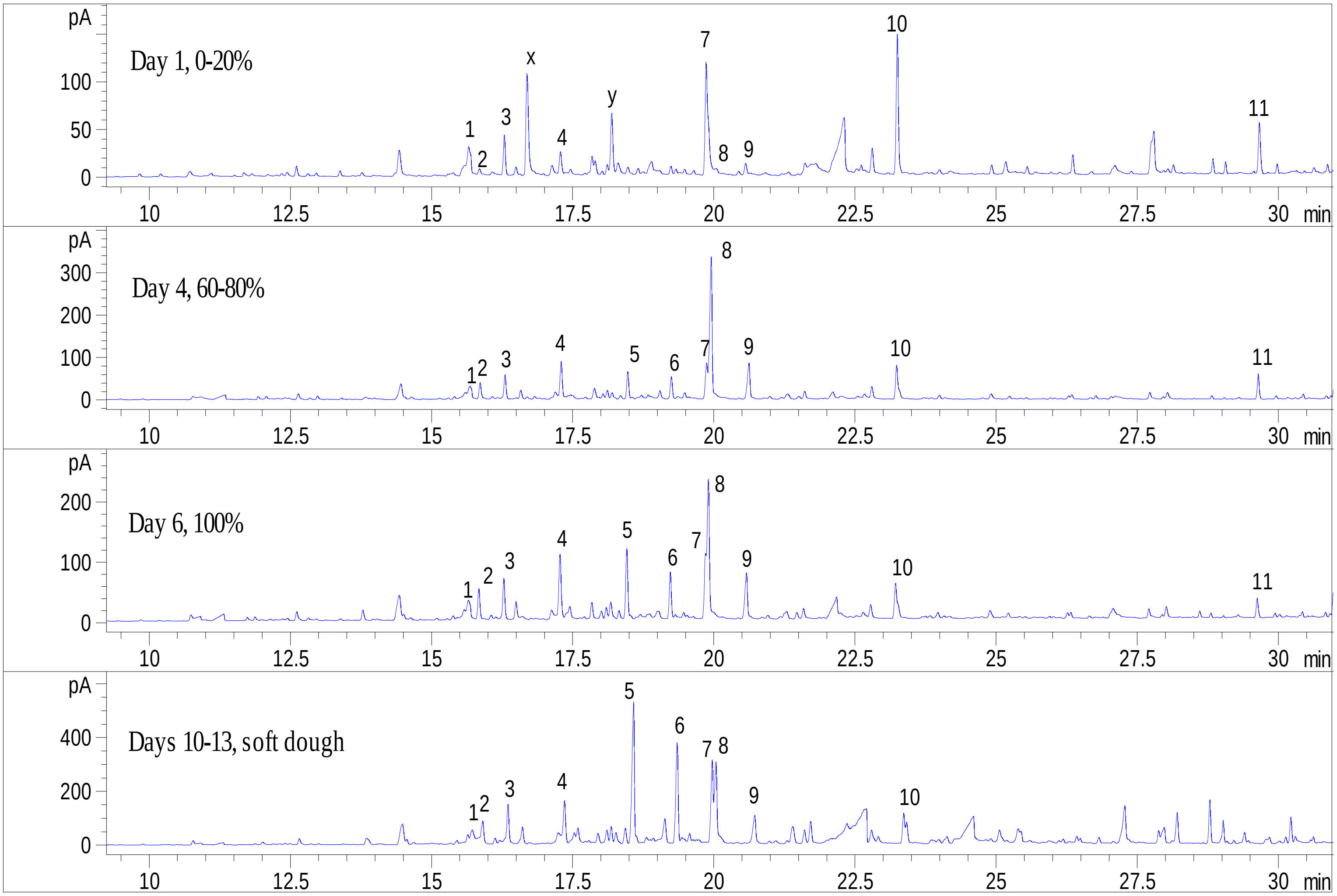
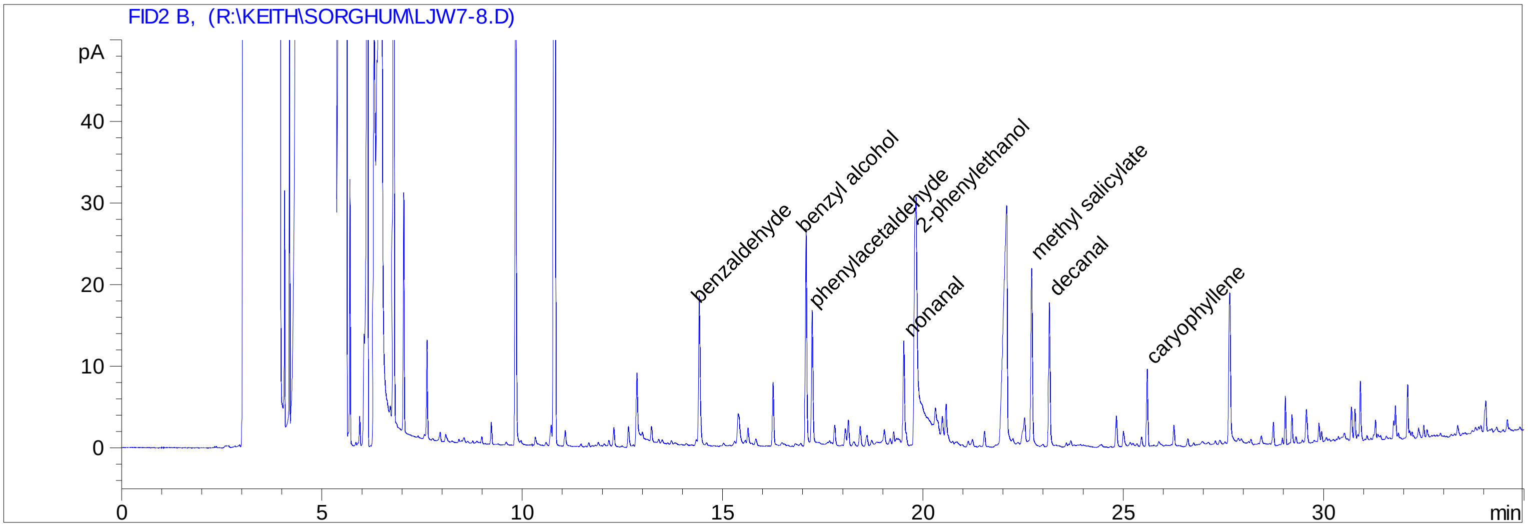


Figure 3b. GC, on HP-1 column, of volatiles collected on Tenax from sorghum (cv. Marcia) flower head (100% flowering) during 24h entrainment



Outputs: 4. Improved ABC management strategies developed and promoted.

4.1 Social context: Survey of farmers' perceptions and ABC control practices.

In April 2000, with support from local extension staff, the project conducted a farmer survey at 4 villages: Shoshong and Makwate in Central region and Shashe Mooke and Marapong in Francistown region. The full survey report is attached to this report as Appendix 1. A follow-up survey planned to assess farmers' success in applying prescribed ABC control methods was not feasible since there were so few ABC in 2001 and 2002. However, the ABC demonstration/training day in April 2002 was used as an opportunity to interview farmers from all over Botswana and receive their views of the potential ABC control methods promoted by the project.

Methods.
In the 2000 survey, farmers were consulted by two principal methods: 1) PRA group exercises conducted at four village gatherings (attendance ranged from 14-54 farmers) and 2) semi-structured interviews with 57 individual farmers (pre-selected to represent a cross-section of farm types), mostly conducted on-farm.

In 2002, following the demonstration and discussion of a range of ABC control measures, 60 farmers, representing 18 agricultural districts, were individually interviewed with the aid of a questionnaire focusing on technology adoption.

Summary of Findings.
The 2000 survey re-emphasised the sporadic, geographically patchy nature of ABC infestation. Many parts of Central region were reported to be severely affected by ABC, but the Francistown region generally was not, although some farmers there remembered outbreaks dating back >25 years ago. Partly as a result of the survey, subsequent collaborative research working with farmers in Shoshong was planned.

- **ABC is considered the second most damaging crop pest, just behind quelea.**

Known locally as "*Setotojane*", ABC was considered a serious pest in Central region. Both at Shoshong and Makwate farmers rated ABC the second most damaging crop pest, just behind quelea. Many complained that the cricket is more of a nuisance than quelea because it cannot be scared away.

Several environmental factors and farming practices were identified which farmers felt might influence ABC populations. There was no agreement, however, on what factors promote an ABC outbreak and no accepted method of forecasting.

- **Farmers’ knowledge of ABC was generally poor.**

The survey identified some important misconceptions about the ABC life cycle and behaviour. A need for awareness-raising was recognised, and this was addressed subsequently by the project's national radio broadcasts during the 2001 and 2002 field seasons and at the demonstration/training day in April 2002.

- **None of the control measures practised were considered effective.**
- **There is widespread, passive acceptance that nothing can be done against ABC.**

None of the commonly practised control measures for ABC in the areas that were surveyed were considered to be effective in an ABC outbreak. The farmers' attitude was generally one of passive acceptance of the problem. Most farmers find ABC repulsive, and the fact that more ABC are attracted (for cannibalism) where one has been killed has led to a common belief that these insects are sent as a punishment from God/the gods. There was a widespread feeling that nothing can be done against ABC, and that they should be left alone.

71% of farmers had at some stage used one control method or another against ABC. These included: hand picking, clean weeding, traditional rituals, frying and scattering ABC in areas of infestation, digging trenches at field margins, clearing a bare strip around fields, using wire fencing rather than brush wood around fields, and spraying.

Some of those farmers who hand-picked ABC fed them to their chickens. This seemed to be a doubly beneficial solution but, surprisingly, others said their chickens would not eat ABC. Washing the dead crickets, to remove their defensive chemical exudate, may be critical for palatability and this aspect requires further investigation.

The survey highlighted certain important characteristics of the farming systems that should be considered when developing appropriate control measures:

- Labour is in a constraint to most households
- Farmers in Botswana are used to a high level of government intervention
- There is a general lack of knowledge of pesticide use
- Some farmers respect taboos on killing ABC

- **Farmers expressed serious safety and environmental concerns.**
- **Surface application of baits was unacceptable.**

Farmers were very concerned about the safety of pesticides and the use of insecticidal baits in the field. This method has been used against ABC in northern Namibia, but was firmly rejected by farmers in eastern Botswana. Most farmers were concerned at the prospect of making up the baits themselves, and were worried that, when placed in the field, the baits could be eaten by domestic animals or children. It was clear that great care would be needed if the bait method was to be developed further. The project subsequently refined the use of baits by developing the baited trench, which uses much smaller quantities of bait presented to maximum effect in the bottom of trenches at field margins. This method received general acceptance following its demonstration at a follow-up survey in April 2002 (see below).

At the time of the first survey the baited trench technique had not been developed. The use of unbaited steep-sided trenches around fields to deter ABC invasion was discussed with farmers, but was viewed by many with some scepticism. Farmers recognised that ABC are proficient climbers. What they did not realise is that whilst the cricket's feet can grip most surfaces, a bare soil face presents a problem because the surface crumbles as the heavy insect tries to climb, and once inside a trench ABC have great difficulty in getting out again. The drawback with this method, highlighted by the farmers, is that it requires hard labour to dig the trench in the first place, at a busy time of year. The project subsequently investigated mechanical methods to reduce the labour input that is needed for trench digging.

- **Farmers are willing to adopt the baited trench.**

Of the 60 farmers interviewed at the 2002 demonstration day, 84% had not heard of the baited trench method of ABC control beforehand. However, following a very successful demonstration (see Outputs 5), 94% stated they were willing to adopt the baited trench control method during the next ABC outbreak. This was a very satisfactory outcome, especially given the farmers' concerns about insecticide baits.

- **Use of trenches against ABC is more common in sandy soil areas.**

The findings of the second set of interviews supported those of the previous survey regarding control methods currently in use, although a higher proportion of farmers in this case considered they were "successful" in controlling ABC than was previously the case. This more positive response may be due partly to the different wording or manner in which the questions were presented. Interestingly however, farmers from certain areas, *e.g.* southern Kalahari, where the soil is sandier and therefore more easily dug, were enthusiastic users of unbaited trenches against ABC, and claimed to have trapped large numbers of crickets using this method. If methods to make trench digging less laborious can be deployed in places where the soil is less amenable to digging then ABC control techniques using trenches could be more widely adopted. The survey found no relationship between the principal control measure currently used by individual farmers and their age nor the local severity of the ABC problem.

4.2 Bait-based methods of ABC management.

4.2a Bait formulation.

Trials were conducted to establish an effective bait formulation for use against ABC. A satisfactory bait would be attractive, palatable and toxic to ABC. Although surface bait application was unacceptable to Botswana farmers, an acceptable, bait control method, the baited trench, was subsequently developed (see below). Long range attraction is less important in this control method, since crickets naturally move along the narrow trench and so will encounter any bait present. However, even under these confined conditions crickets are likely to exercise some selectivity before feeding and so the benefits of a bait with high palatability still apply. Selection of an effective, affordable, environmentally benign insecticidal agent remains critical to the success and acceptability of this control method.

Methods.

The palatability of a range of potential bait carriers was compared. ABC were starved for 3 hours and then placed in individual laboratory cages containing a weighed amount of one from the following potential bait carriers: maize meal, maize bran, sorghum bran, millet bran, or one of these three cereal brans mixed with powdered dried ABC. Fresh bait was provided daily and individual consumption rate monitored for 96 hours. Water-soaked cotton wool was also provided.

The oral toxicity of eight insecticides was assessed, each for at least 5 concentrations, using maize meal paste as the bait carrier (Table 4.1). In this case 10-15 crickets were placed together in a large glass topped cage containing the bait. Treatments and controls were replicated 5 times, with totals of 25-50 insects used per concentration. Mortality was recorded by inspecting crickets individually 24 hours after they were placed in their cages. Probit analysis was used to calculate LD50 and regression statistics.

Table 4.1 Insecticides tested for oral toxicity to ABC, with dose ranges.

Active ingredient	Trade name	Dose range (ug/g carrier)
Fipronil	*Reagent 200*	0.00007-0.03
Cypermethrin	*Avisipermethrin*	0.03-0.7
Chlorpyrifos	*Dursban 480*	0.07-1.0
Imidacloprid	*Gaucho 700*	0.5-233
Cyfluthrin	*Baythroid*	3.3-75.8
Carbaryl	*Karbasprays 850*	28.3-2833
Gamma-BHC	*Gamma 120*	100-2000
Malathion	*Malasol 500*	104-8333

Results.

- **Sorghum, maize and millet brans are equally acceptable as bait carriers.**

No significant differences in consumption rate were detected between the seven bait carriers (Figure 4a). Inclusion of dried ABC did not affect bait palatability significantly, although millet bran + dried ABC was the most consumed bait carrier. These findings suggest that farmers could use any available cereal bran as the bait carrier.

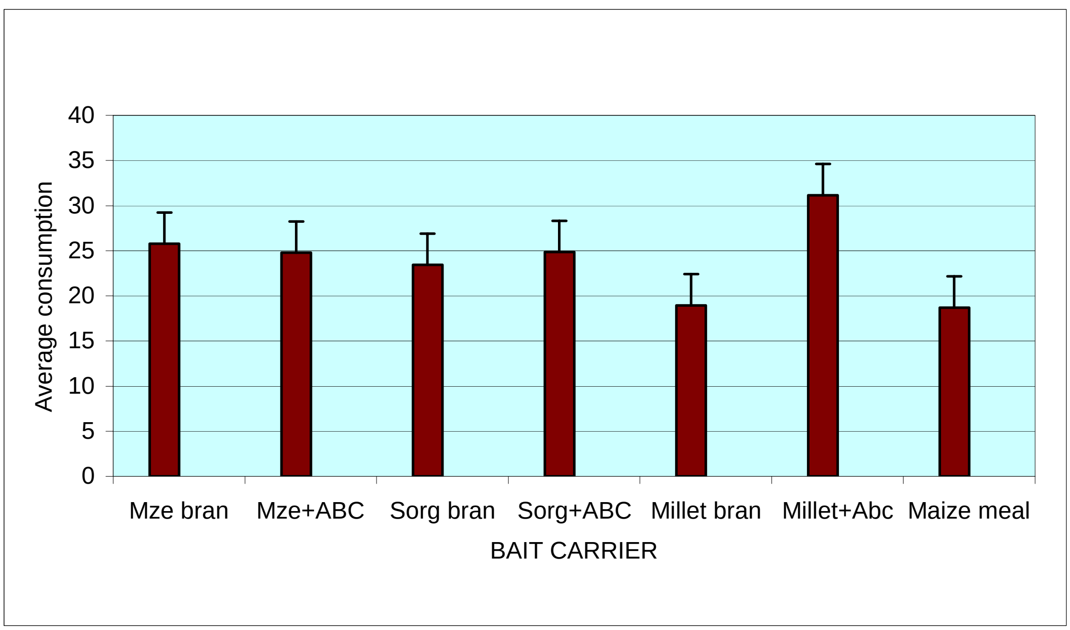


Figure 4a. ABC bait carrier consumption rates (dry weight/day).

- **8 insecticides were tested at a range of concentrations for oral toxicity to ABC.**

The findings of the insecticide assessment are summarised below in Table 4.2.

Pesticide	**Group**	**LD50** (95% fid.limits) (μg/g)	**LD90**	**Slope** (SE)
Fipronil	Pyrazole	**0.05** (0.009-0.1) [a]	0.23	2.00 (0.30)
Cyfluthrin	Pyrethroid	**0.52** (0.25-0.92)[b]	2.60	1.83 (0.24)
Imidacloprid	Neonecotinoid	**1.24** (0.54-2.83)[bc]	7.60	1.63 (0.28)
Cypermethrin	Pyrethroid	**2.30** (0.87-3.40)[bcd]	12.6	1.7 (0.32)
Chlorpyrifos	Organophosphate	**4.50** (0.58-16.3)[bcde]	23.0	1.8 (0.36)
Carbaryl	Carbamate	**5.00** (2.60-8.90)[cdef]	56	1.25 (0.16)
Gamma-BHC	Organochlorine	**20.00** (17.0-25.0)[g]	60	2.7 (0.35)
Malathion	Organophosphate	**21.10** (19.0-24.0)[gh]	197	1.3 (0.172)

Table 4.2 Dosage-mortality data of eight insecticides against the armoured bush cricket, presented in order of toxicity

SE = Standard error of slope; LD50 values with same letter are not significantly different from each other

Fipronil is acutely toxic to ABC and other insects at very low concentrations (LD50=0.05μg/g). Furthermore, it remains active, both by contact and ingestion, for relatively long periods with a half-life of 122-128 days in oxygenated sandy loam soil. Hence, whilst it is an extremely effective ABC killing agent it also poses a sustained environmental hazard to other invertebrates. This aspect is further assessed under Output 4.3 below. Another consideration is that working with extreme low concentrations, as are required with Fipronil, may present farmers with calibration problems during bait formulation. Currently Fipronil is not available to farmers in Botswana.

The pyrethroids cypermethrin and cyfluthrin have a high knockdown ability but show poor stability under UV (Elliot *et al*. 1973). Whilst pyrethroids are environmentally benign, photodegradation under field conditions means they are effective for only short periods and so repeated baiting would be necessary to control ABC during the peak of the field season.

Imidacloprid has moderately sustained activity and it is relatively benign environmentally (Pfuger and Schmuck, 1991). It is not, however, readily available in the local markets in Botswana. Imidacloprid is potentially suitable for bait formulation against the ABC.

Carbaryl is widely used in insect control. It is stable, active at low doses, cheap and readily available to farmers in local markets throughout Botswana. It appears to be the most viable of the candidate insecticides for use in ABC bait.

Chlorpyrifos is the most toxic of the organophosphates tested with an LD50 of 4.5μg/g. It is widely used in agriculture and against household pests in southern Africa, but can have a serious impact on non-target organisms.

Malathion is locally available and quite widely used in Botswana. However due to its pungent smell farmers are very reluctant to use it if any alternative is available. Therefore other pesticides are likely to be more acceptable for use in ABC bait formulation.

Gamma-BHC is widely available and cheap, so is used by many farmers and government agencies in southern Africa. It is persistent in the environment and it is relatively toxic to non-target organisms including humans, however, so it is not the most appropriate insecticide for use in ABC bait formulation.

- **Carbaryl/bran bait is recommended.**

Taking the factors above into consideration, the bait recommended for use against ABC was formulated from carbaryl (85% wettable powder) and cereal bran at a dose rate of 3g/kg for LD90.

4.2b Bait Deployment.

Daily and seasonal patterns of behaviour and movement were evaluated to provide guidance in establishing the most effective deployment pattern of baits in farmers' fields. As discussed above, however, surface application of baits was unacceptable to Botswana farmers. Bait deployment in trenches, as described below, provides an acceptable alternative control method.

ABC movement studies.

Methods.

Movements of ABC were monitored in two ways. First, longer term, larger scale population movements were assessed by monitoring ABC population densities in different vegetation types (4x 25m^2 plots each of: sorghum/maize crop, wild grass areas, *Acacia* scrub and broadleaved weed patches) around one farm throughout the cropping season. Behavioural observations were recorded whilst population monitoring (as *walking*, *resting/basking* and *feeding*), allowing a daily activity pattern to be established for ABC. Secondly, the movements of individually tagged males and females were monitored in farmers' fields. Resighting of individuals was achieved after nightfall using a spotlight which picked out the crickets' reflective tags. Using this method, a comparison was made between ABC movements over 3 days in a field of sole sorghum (59 males and 69 females released) and a field sorghum undersown with climbing cowpeas (43 males and 42 females released).

Results.

- **A daily pattern of movement between habitat types was detected.**

Whilst ABC can be found in all vegetation types at all times of day, statistically significant daily population shifts between vegetation types were observed (Figure 4b; analysis of deviance). *Acacia* scrub was preferred during the early morning but cricket numbers declined there as the morning progressed. By late afternoon cricket numbers in *Acacia* scrub there rose again, peaking soon after nightfall. This was indicative of a tendency for ABC to "roost" at night on both living and dead thorn bushes. Such bushes offer protection against predators, but perhaps more important, they provide safe, elevated basking sites to delay body cooling in the evenings and to speed warming up in the mornings. Crickets aggregated conspicuously on the west side of bushes in the late afternoon and on the east side in the morning.

- **Thermoregulation by basking is a prominent aspect of ABC behaviour.**

Behavioural thermoregulation is certainly very important to ABC, which have a very large body mass by insect standards. Evidence from research on other insects suggests maintenance of an elevated core temperature is likely to increase ABC fecundity substantially. By the same measure, overheating is a problem for large insects, and ABC actively sought shade during the hottest part of the day. This may partly explain the observed increase in population density amongst the shady broadleaved weed patches and crop plants and coincident decrease on the more exposed wild grasses, during the middle of the day.

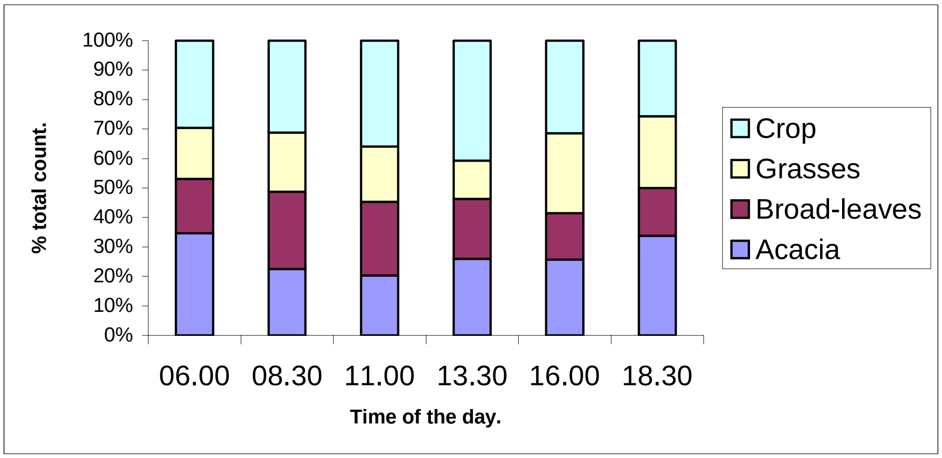
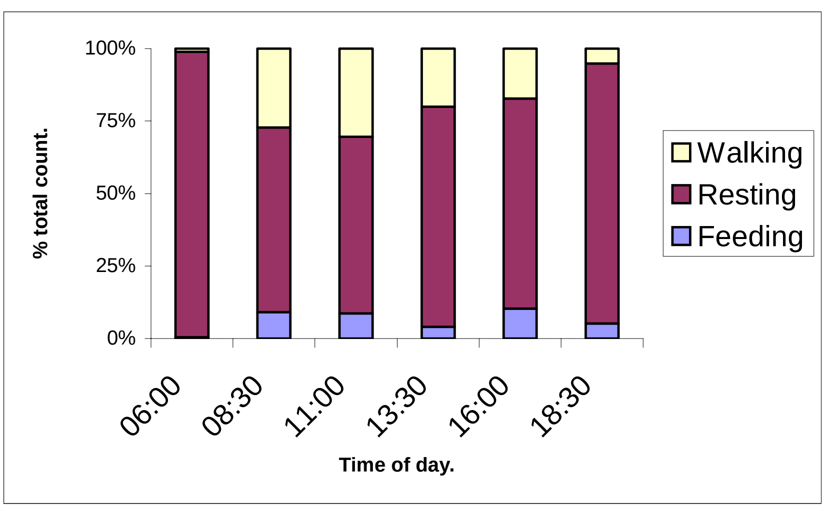


Figure 4b. Daily changes in ABC population density in different vegetation types.

Behavioural records confirmed that basking ("resting") was predominant in early morning and late afternoon (Fig. 4c). Typically, crickets migrated out of the roosting bushes soon after 07.00h to forage. Feeding peaked at around midday. A decline in observed feeding and walking in early-mid afternoon may be related to ABC remaining in the shade to avoid overheating (observed increase in "resting"), but by 16.00h feeding increased again, before crickets started to return to their roosting sites.

Figure 4c. Simple classification of ABC behaviour through the day.



- **ABC invade crop fields at the time of panicle emergence.**

Viewed over a longer time period, a significant movement of crickets was detected, by means of population density monitoring, from *Acacia* scrub into crop fields between 50 and 60 days after crop planting (Fig. 4d). This is the "field invasion" which coincides with sorghum panicle emergence and represents a population movement from the nymphal habitat into a favoured adult feeding habitat.

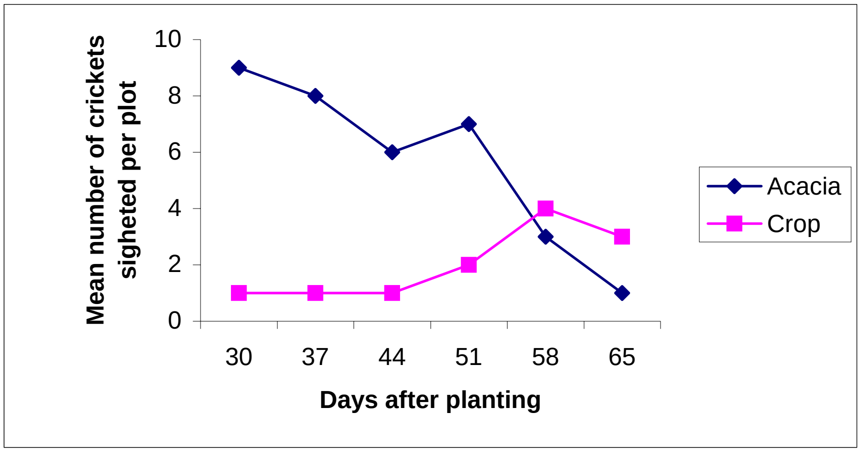


Figure 4d. Population density changes in *Acacia* scrub and amongst crop plants over the growing season

In the comparison of ABC movement in sole and mixed crop fields, both systems had highest number of cricket resightings at the first observation time, 24 hours after release, declining thereafter (Fig. 4e)

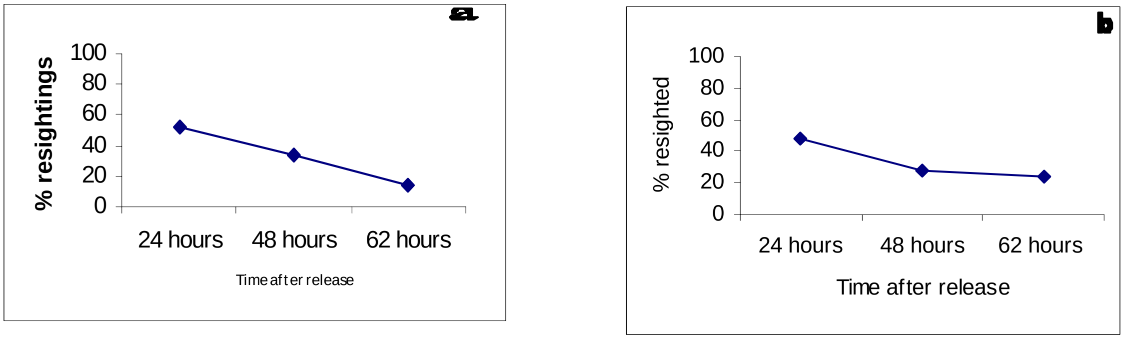


Fig. 4e. Mean percentage of the total number of ABC resighted during the trial period (a) in a pure sorghum crop and (b) in a sorghum/cowpea mixed crop.

Repeated censuses of the distribution of marked individuals showed a decline in the number of crickets lost with time, but there was no significant difference in loss rate between the two cropping systems (Sole: 0.53±0.08, Mixed: 0.42±0.15, t=2.31, n=12, p=0.53).

- **Dispersal patterns of males and females differ between sole and mixed crops.**

In the sole crop there was no significant difference in daily displacement between males and females, both sexes averaging approximately 8m/day. In the mixed crop, however, daily displacement was significantly greater in males than in females (t=2.17, n=18, p=0.03) (see Table 4.). In fact, compared to the situation observed in sole sorghum, average male daily displacement was greater in the intercrop and female daily displacement lower in the intercrop. Mean (±SD) daily displacement between the two cropping system was not significant (t=2.05, n=43, p=0.95), but this aggregated statistic masks the underlying sex difference in dispersal in the two cropping systems.

Table 4.3. Daily dispersal distances of marked ABC in mixed and sole cropping systems

Cropping system	Sex	Released	Mean daily displacement (m)	Maximum daily displacement (m)	Loss rate (/day)
Sorghum/Cowpea	M	43	12.66±3.56	44.3	
	F	42	3.14±1.30	8.09	
	Total	85	7.59±2.17		0.42±0.15
Sole Sorghum	M	59	7.31±1.64	25.12	
	F	69	8.32±1.57	26.72	
	Total	128	7.76±1.14		0.53±0.08

Dispersal quartiles, based on distribution of ABC after 24 hours, are presented in Table 4.4. On average 50% of males and females dispersed ≤ 12.35 m and ≤ 10.51 m respectively in the sole crop, whereas 50% of males and females dispersed ≤ 8.20 m and ≤ 0.40 m respectively in the mixed crop.

Table 4.4. ABC dispersal quartiles (m) in mixed sorghum/cowpea and sole sorghum fields

Cropping system	Sex	Dispersal quartiles (m)			
		25%	50%	75%	100%
Sorg/CP Mixed	Male	0.25	8.20	17.09	32.15
	Female	0.0	0.40	5.06	8.09
Sole Sorghum	Male	0.42	4.58	12.35	25.12
	Female	2.68	6.54	10.51	25.88

These findings suggest that the nature of the crop field can have a major bearing on ABC dispersal. In the structurally more heterogeneous mixed sorghum/cowpea crop habitat, ABC exhibited a strikingly different dispersal pattern compared to that seen in more homogeneous sole sorghum. In the mixed crop female ABC tend to aggregate in areas with dense patches of cowpea. Such patches may be favourable for feeding opportunities, safe basking sites and shade. Our tentative interpretation is that males may be responding to female aggregation by switching from a strategy of acoustic mate attraction (“stand and sing”) to one of active mate-searching, seeking out female groups. Female aggregations are similarly observed in weedy sorghum fields, amongst denser weed patches, and so it is likely that male dispersal is also greater in such fields compared to well-weeded sole crops.

Since surface application of baits is not a sociologically acceptable option in Botswana, theorising over spacing and positioning of baits was not appropriate. But at the very least, the present findings suggest that the nature of the field can be critical to the pattern of ABC movement. Most crop fields in SE Botswana do include patches of weeds and it would seem advantageous that, if surface baits were to be used, they should be positioned in and around denser weedy patches in places where females are likely to aggregate and males are likely to visit, as well as at field margins to attract incoming ABC.

The baited trench.

Despite the advantages baits offer in terms of cost effectiveness and targeting ABC specifically, surface application of baits was not acceptable to farmers in Botswana (see above). Initial studies on the use of trenches to intercept ABC as they migrated into the field were promising. However, the addition of small quantities of bait (formulated for surface application) to the bottom of the trench significantly enhanced the effectiveness of this control method, as described below.

Methods.

Vertical-sided trenches were constructed around three bare plots of 4m x 3m, located in a large sorghum field with consistent soil texture at Sebele Research Station. Flowering sorghum plants were present approximately 1m beyond the sides of each plot. Trench depths were: 20cm, 30cm and 50cm; trench width was 20cm, corresponding to the width of the standard trench digging tool used by farmers. Following 6 hours of food deprivation, 36 crickets (1:1 sex ratio) were released on each enclosed plot (3 crickets/m^2 corresponds to outbreak population density). The crickets soon moved out towards the sorghum and duly fell into the trenches. In certain plots the ABC were checked at 3 hour intervals; in all plots the number of ABC remaining in the trench was counted after 24 hours. 5 replicate trials were conducted for each trench depth. This procedure was repeated subsequently, but with the addition of 2.5g teaspoons of bait carrier (moistened maize bran) or bait (same, but containing 3g/kg carbaryl) at 3m intervals along the trench bottom.

Results.

When crickets first fell into a trench they attempted to climb out. Although ABC are excellent climbers of vegetation and firm surfaces, they found it difficult to climb the near-vertical soil face of the trench because surface particles crumbled away under their tarsi, resulting in a fall. Escape from a trench was usually achieved by scaling a favourably firm, creviced section of trench wall or, under typical field conditions, by means of overhanging vegetation that dips into the trench, *e.g.* a grass stem. What was usually observed was that the cricket attempted to climb up the wall of the trench around the point of entry, and then after some minutes it walked along the trench and tried elsewhere. After 1-2 hours ABC escape efforts diminished and the crickets investigate potential food items. In the case of the 300mm baited trenches (Fig. 4f) ABC retention was monitored at 3h intervals and the retention levels reflected the switch from escape to feeding on bait, followed in this case by death.

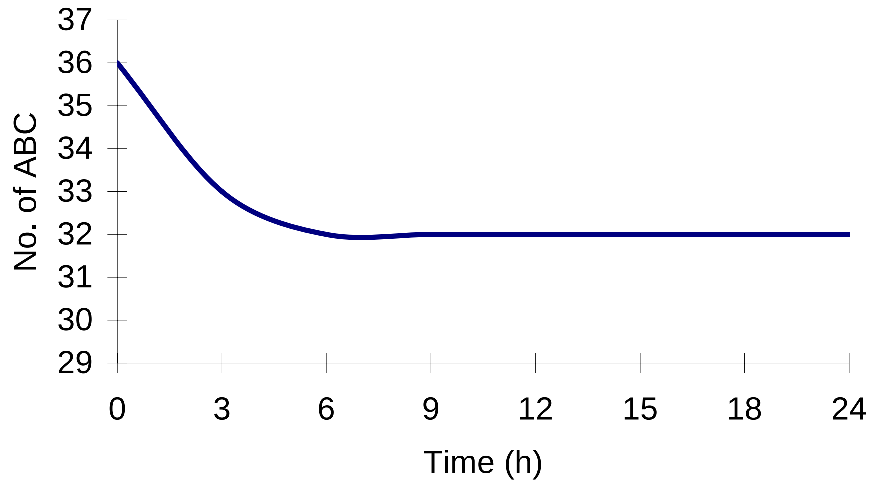


Figure 4f. Mean ABC retention in 300mm baited trenches over time

Results from the trench trials are summarized below in Figure 4g. In the empty, unbaited trenches, there was a significant increase in retention with each increase in depth. The same trend applied in the case of trenches containing bait carrier although, surprisingly, retention levels were lower at each depth than for the empty trenches. Possibly the food consumed helped crickets to make more vigorous efforts to escape. In the case of trenches containing bait, ABC retention levels were significantly higher than in the other treatments at each trench depth. In this case, however, there was no significant difference in retention levels for trench depths of 300mm and 500mm, which on average retained 93% and 94% of ABC respectively.

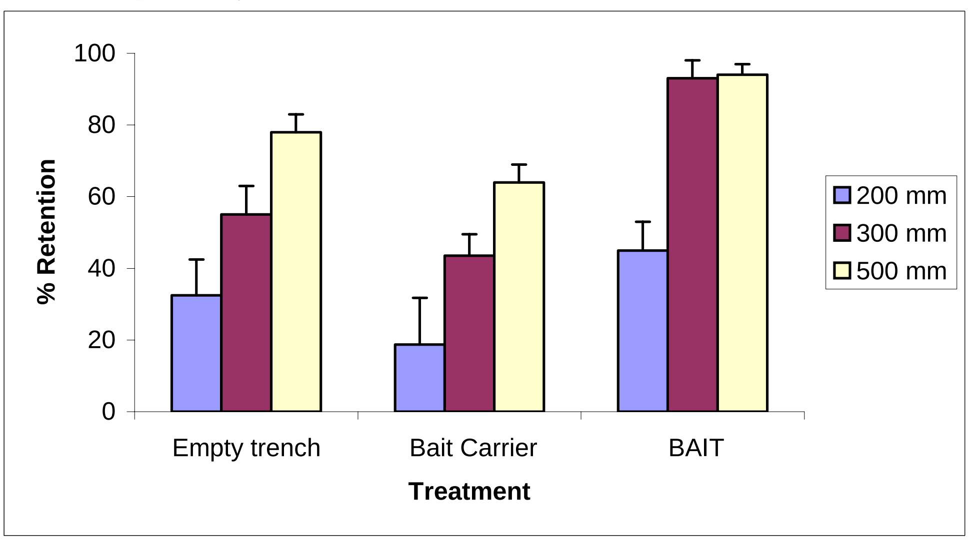


Figure 4g. ABC retention in experimental trenches

- **A baited trench of depth 300mm provides effective ABC retention.**

The present findings suggest that, under field conditions at Sebele at least, a trench depth of 300mm is adequate for the baited trench to function effectively, and that deeper excavation is not worthwhile given the extra labour input needed.

An extensive set of trials was set up in 2001 to assess the effectiveness of different bait presentation methods used at field edges, comparing surface baits, baited trench, unbaited trench and baited thorn bush branches. Unfortunately, ABC numbers in that season ultimately were not sufficient to conduct the trials.

Further testing in different soil types under outbreak conditions is needed, but the baited trench is certainly the most promising control method developed for use against ABC. The project's farmer training day included a successful demonstration of the baited trench, and now farmers from locations all across Botswana are ready to try out this method when the next ABC outbreak occurs.

Labour constraints and mechanisation of trench digging.
The labour requirement is a significant disincentive to farmers considering trenches as an ABC control method, although on the evidence of the second farmer survey, this appears to be less of a problem in sandy soil areas. Therefore, preliminary investigations were made on the use of mechanised tools for trench digging.

- **Mechanical means of trench digging were investigated.**

Mechanical trench digger. A prototype tractor-mounted trench digger was designed and manufactured by the agricultural engineering workshop at Sebele Research Station (Fig.4h), using many scrap components. This digger is essentially a very basic version of commercial trench diggers. Chain-mounted, hardened steel scrapers excavate the trench and soil is directed away from the trench by rotating screws. The tool produced well-formed vertical-sided trenches in both tilled and compressed soils at Sebele and Shoshong. Manufacture is beyond the scope of individual farmers since an engineering workshop is needed and the cost of components would be prohibitive. However, the possibility has been discussed that a number of such diggers could be manufactured and distributed to regional extension offices ready for use when scouting suggest an ABC outbreak is imminent. Whether or not this happens, the digger could prove particularly effective where larger fields of cereal border onto *Acacia* scrub.

Figure 4h. Tractor mounted trench digger.

Modified plough. Adjustments were made to the mould board of a conventional plough in order that it produced a furrow with one steep side (approx 70^{o} from horizontal). Tests suggest that with the steep side of the furrow adjacent to the field, field entry by ABC was reduced by approximately 30%. These findings are preliminary, however, and further improvements may be possible. Whilst this method is currently somewhat less effective than the trench, the "steep furrow" has the advantage that it can be ploughed using animal traction rather than a tractor, so it is a more feasible option in poorer areas.

Twin cutting discs. A simple tool to aid trench construction, which was designed but ultimately neither constructed nor tested, consists of two bracket-mounted hardened steel blades or discs, spaced 200mm apart. These could be drawn behind a tractor or a donkey, and loaded to make parallel deep vertical cuts into the soil. The soil between the cuts would be dug out subsequently by spade to produce a vertical sided trench. This method of trench construction still requires a significant labour input, but this would be considerably less laborious than trench construction using a manual trench-digging tool. Furthermore, the tool would be simple enough for construction in a rudimentary workshop provided suitable material to make the blades was available. In areas with hard, compressed soil this simple tool might make trench construction feasible where otherwise it would not be.

4.3 Impact of insecticidal residues from baits and barrier spray on non-target invertebrates.

Environmental concerns were surprisingly high amongst Botswana farmers that were interviewed in relation to ABC control. When they were told the project would assess the effects of insecticidal baits and spray on other animals this was met with approval.

Methods.

The short-term effects of carbaryl bran baits and fipronil barrier spray (as used to control ABC) on non-target insects were monitored in field trials at Sebele Research Station. Fifteen 10m x 5m plots were subjected to one of five treatments, namely: 1) carbaryl bait applied uniformly in the trial plot, 2) fipronil cover spray, 3) carbaryl bait applied in a trench, 4) fipronil barrier spray and 5) control, each being replicated three times. The plots were separated from each other on all sides by 3 m. Details of the formulations, dose rates, and rates of application of the compounds are given in Table 4.5.

Table 4.5. Formulation, dose and volume of application for the two test compounds.

Common name	Chemical name	Formulation	Application rate (g a.i.ha^{-1})
Carbaryl	1-Naphthyl methyl carbamate	850 g kg^{-1}	11(field perimeter)
Fipronil	(±)-5-Amino-1-(2,6-dichloro-4-trifluoro-methylphenyl)-4-trifluoromethyl-sulfinylpyrazole-3-carbonitrile	200 g l^{-1}	28.80

Fipronil 200 EC was applied with a backpack sprayer. Carbaryl bait was applied in 2.5g teaspoons at three metres intervals inside a 300 mm deep trench that surrounded the plot. Cover applications of bait and fipronil spray were applied to entire plots in an attempt to simulate a “worst case” situation of the technologies.

The invertebrate fauna was sampled 48 hours pre- and post-treatment using pitfall traps, sweep netting and light traps. The pugnacious ant, *Anoplolepis custodiens* (Smith) (Formicinae), which forms a conspicuous faunal component of the field and ground layer in Botswana, was selected as the principal indicator organism. Longer-term effects of bait and barrier treatments were evaluated using this species; counts of active ant burrows along five 10 m x 1m transects in each plot were used as a means of monitoring ant abundance at timed intervals following application. An active burrow was defined as one with at least five ants entering or leaving the burrow during a period of observation.

Summary of Findings.

The pre-treatment abundance of invertebrates in the cover application plots is shown in Fig. 4i. Pugnacious ants and ground dwelling tenebrionid beetles made up most of the pitfall trap catch.

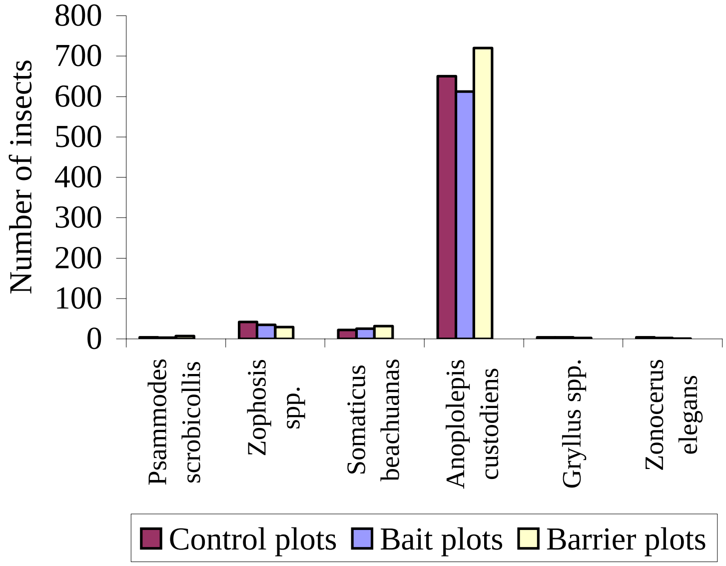


Figure 4i. Abundance of common species recorded in plots 48 hours before treatment.

Figure 4j shows the abundance of insects sampled 48 hours after cover application of carbaryl bait. The broadcast application of bait resulted in a small but significant reduction in abundance of *A. custodiens*, but otherwise had no effect insect abundance.

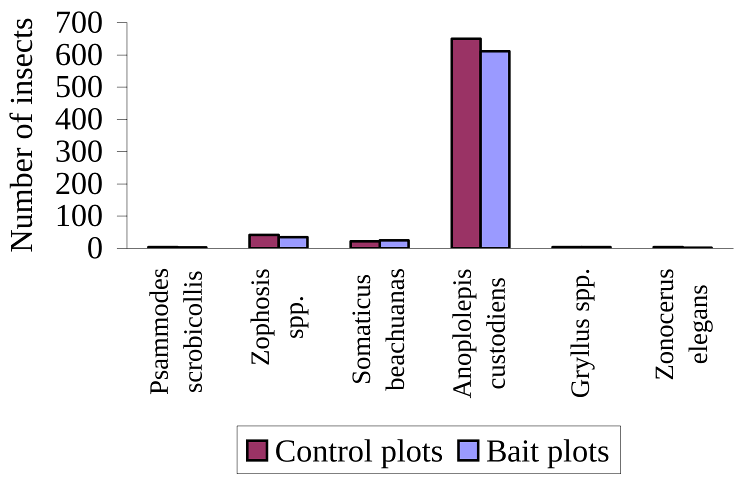


Figure 4j. Abundance of species recorded on control and baited plots 48 hours after cover application carbaryl bait.

A severe reduction in the numbers of all arthropods occurred in plots subject to cover spray with fipronil. Figure 4k illustrates insect abundance 48 hours after cover spray application. Tenebrionid beetles were completely eliminated in these plots.

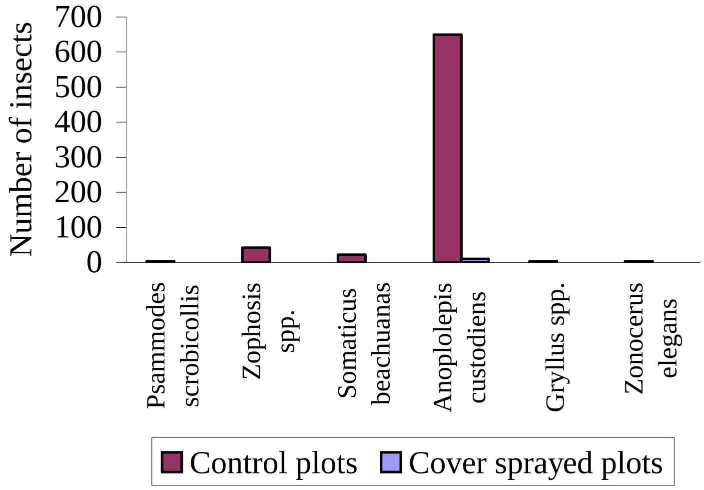


Figure 4k. Abundance of species recorded on control and cover sprayed plots 48 hours after fipronil application.

Longer-term observation of ant activity showed that ant activity in carbaryl baited plots had recovered 10 weeks after bait application. Ant activity in plots cover sprayed with fipronil, however, failed to recover during the eight months of study (Fig. 4l, overleaf). Ant activity declined to minimal in August and September due to dry, cold winter conditions.

Considering the impact of carbaryl baited-trench and fipronil barrier spray treatments, neither had a long term impact on the ant populations. After an immediate reduction following application, a return towards control population levels was observed 4-6 weeks later in both treatments (see Fig. 4m).

Baited-trench and barrier strip spraying techniques both had a relatively transient impact on the ant populations. A return to activity levels close to those seen in control plots was observed four to six weeks after application in both treatments and field observations suggest the impact probably occurred through a reduction in worker numbers rather than colonies being completely destroyed in the vicinity.

Provided they are applied at the correct time, both of these techniques target ABC as the crickets invade crop fields, at the time of panicle flowering. The present findings suggest the two measures could be used to control armoured bush crickets with little impact on non-target invertebrates and the environment generally. ABC appear to have few natural enemies, but one which farmers recognise as an ally against the *Setotojane* is Abdim's stork (*Coconia abdimii*). When baited trench and barrier spray are deployed during the next ABC outbreak it will be important to monitor the behaviour of storks and any other scavengers, since a concern arises over potential knock-on effects through consumption of dead and moribund crickets, which are likely to accumulate around the field margins.

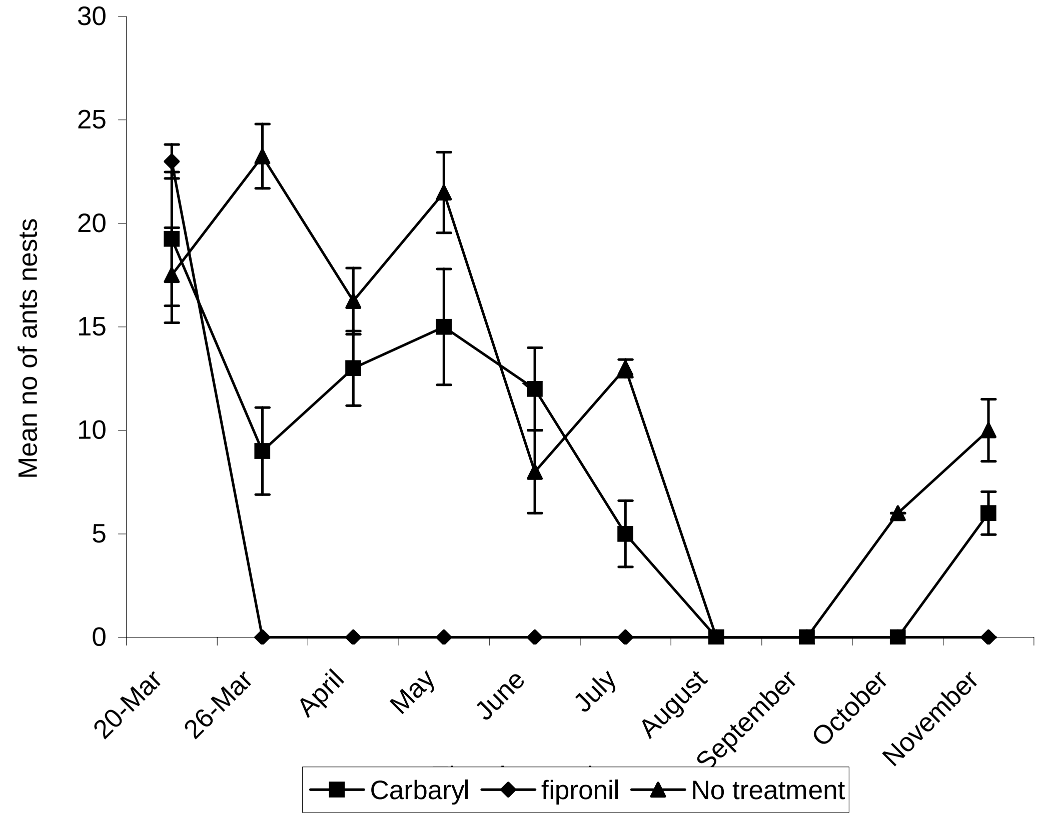
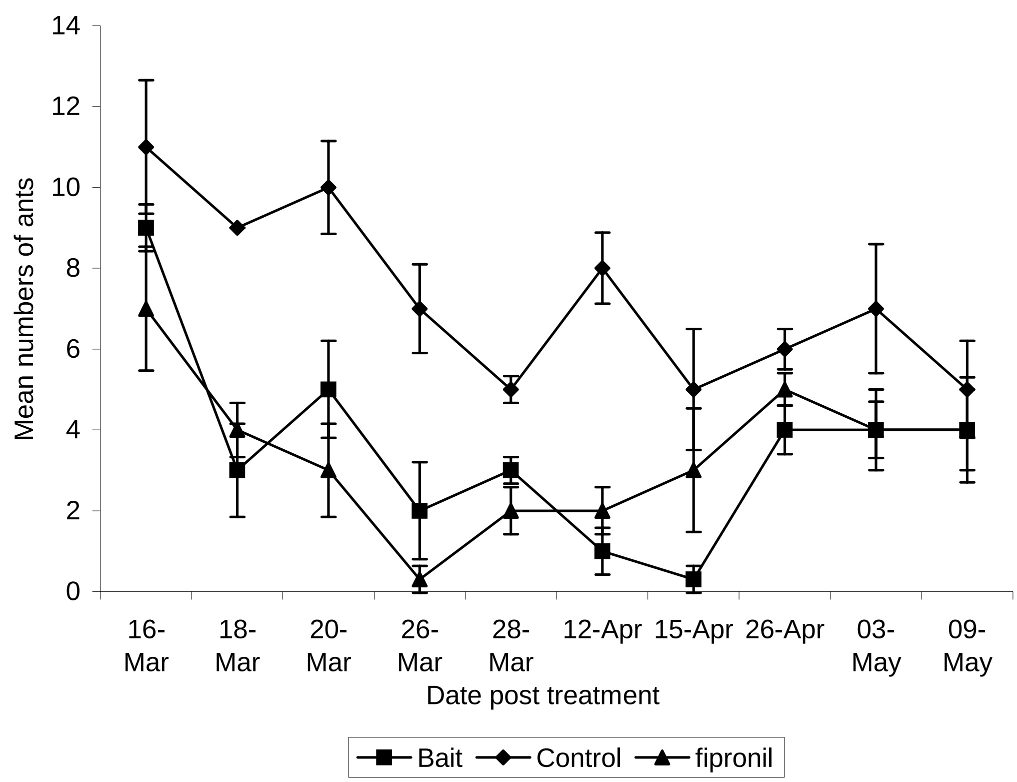


Figure 4l. Effects of cover application of fipronil spray and carbaryl bran bait on numbers of active burrows of pugnacious ants between March and November 2001. Bars indicate standard errors.

Fig 4m. Mean numbers of active ant burrows in plots subjected to baited trench and fipronil barrier spray at Sebele between March and May 2002.



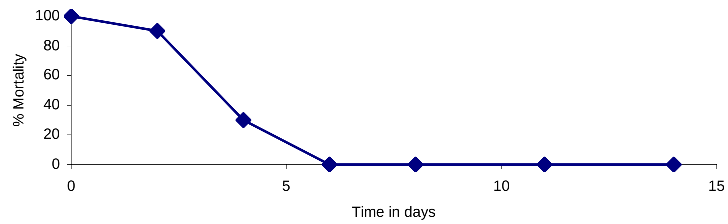
4.4 Barrier spraying at field edges as an ABC control strategy.
Application of a persistent insecticide in a sprayed strip around fields can be a cost effective, environmentally benign control strategy against insects that will predictably cross the barrier strip. The effectiveness of this technique was tested against ABC using fipronil, which is recognised as both potent and persistent, on the rationale that if the technique can be effective against ABC then it should work when fipronil is used. The following study was conducted during the 2000 ABC outbreak.

Methods.
The effective application rate for fipronil against ABC was first determined thus. Five enclosure cages (4 m^2) were set down in an area of uniform soil and low vegetation and four different dose rates of fipronil were evaluated, using water as the control. Dose rates tested were: 20 ug/ai, 50ug/ai, 70 ug/ai and 90ug/ai, corresponding to 50 $mgha^{-1}$, 125 $mgha^{-1}$, 175 $mgha^{-1}$ and 225 $mgha^{-1}$ respectively. Spray was left to dry for 2 hours inside the cages, before ten adult ABC were added to each cage. Previous observations suggested that the crickets take an average of 30 minutes to cross the non-cultivated space (typically c.3m in width) left by farmers between the surrounding vegetation or any fence and the crop. Therefore the ABC were left in test cages for 30 minutes before removal to observation cages in the lab, containing food and water. Mortality was recorded at 48hours and 72 hours. Those dose rates that gave mortality rates of >70% after 72 hours were considered effective.

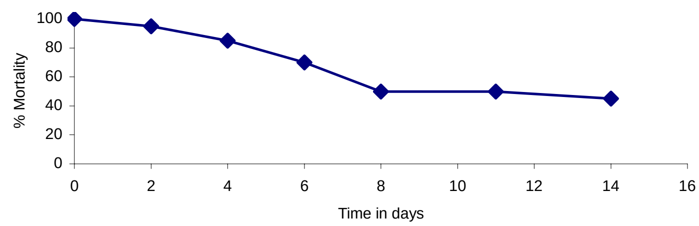
Residual toxicity of the different fipronil doses applied was evaluated over 2 weeks, with observations made on days 0, 2, 5, 8, 11 and 14 post spraying. Fifty ABC were used for each dose rate for each observation, each being replicated 3 times. A second study was conducted in cages enclosing either wild grasses or sorghum plants, to assess residual toxicity. Fipronil was applied to grass or crops at 175g-ai ha^{-1}. Three cages were used for each treatment, each being replicated 3 times. Insects were introduced for 30 minutes, as previously, in the cages at 0, 2, 4, 7, 11 and 14 days post treatment, before removal to the laboratory, as previously.

The effectiveness of barrier treatment with fipronil was assessed using six 20m x 10m plots, separated by a 5m buffer zone, in a field of flowering sorghum (average plant density 4 plants/m^2). One side of every plot was the field edge, bordering onto an area of *Acacia* bushes, which served as a continuous source of ABC to invade crops. Six further 20m x 10m plots were set up and ABC counted and removed from the site daily, to monitor the invading population. In treated plots, ABC were counted and removed only 24hours before barrier spraying. Fipronil was applied at a rate of 175 $gaiha^{-1}$ in a barrier strip 3m in width. ABC numbers and levels of sorghum damage was monitored in the experimental plots at intervals over 2 weeks. A minimum of 100 randomly selected sorghum plants were sampled in each plot on each occasion, the number of ABC on plants and on the ground within an arm’s range were scored.

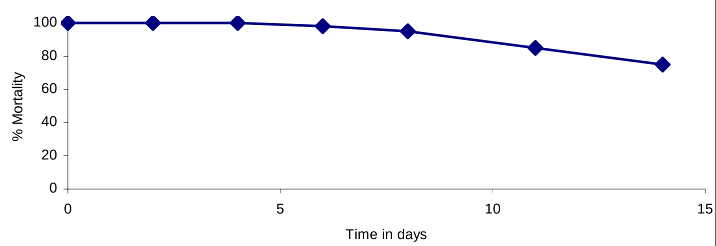
Figure 4n. Efficacy of different fipronil application rates, after spraying.



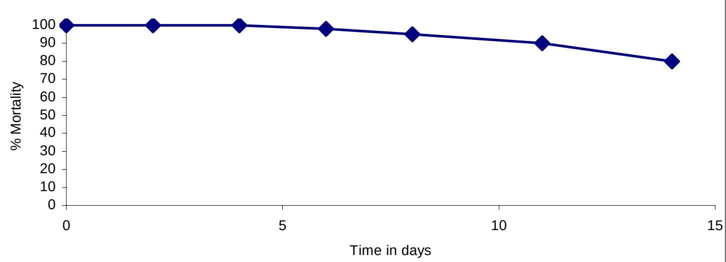
Efficacy of fipronil applied in cages at **50 g-ai/ha**



Efficacy of fipronil applied in cages at **125 g-ai/ha**



Efficacy of fipronil applied in cages at **175 gai/ha**



Efficacy of fipronil applied in cages at **225 gai/ha**

Summary of findings.

The four concentrations of fipronil tested gave mortalities of 0%, 45%, 78% and 80% after 2 weeks of spraying (Fig. 4n, previous page). Only applications rates of 175 $g\text{-}aiha^{-1}$ and 225 $g\text{-}aiha^{-1}$ gave effective barriers for 2 weeks, and hence the former is recommended for ABC control.

Figure 4o illustrates that fipronil residual efficacy did not differ significantly between substrate types. Both the sorghum and grass substrates retained adequate residues to cause >70 % mortality 2 weeks post treatment.

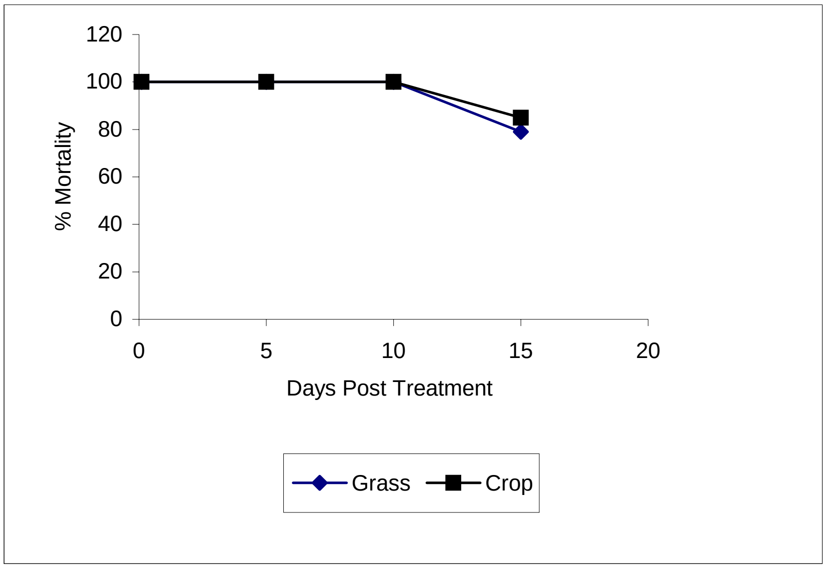


Figure 4o. Effectiveness of fipronil sprayed on crop sorghum and grass as a barrier treatment against ABC

The average number of ABC in the treated plots was 3-fold lower than ABC numbers in the control plots throughout the observation period (Fig. 4p). The entry rate of ABC into an adjacent set of plots was found to average >60 ABC/plot/day over a period of six days.

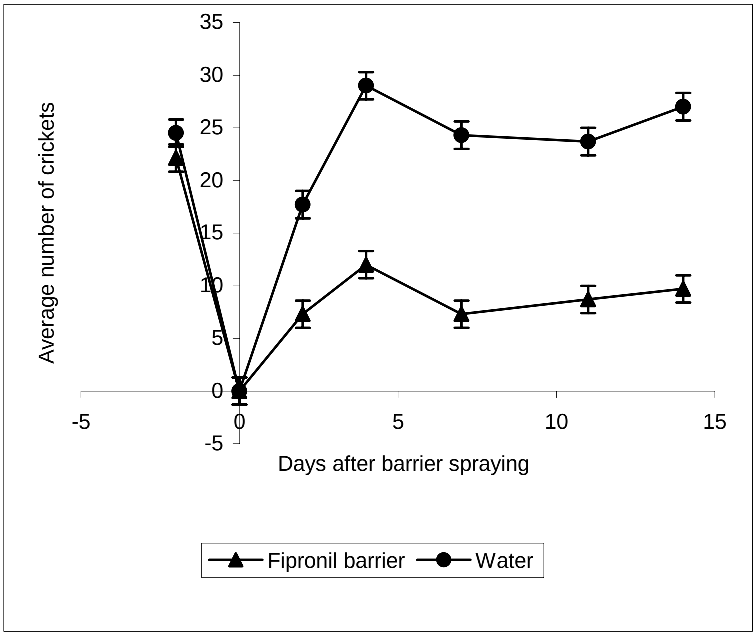


Figure 4p. Incidence of ABC in treated and control plots.

Unfortunately, comparative estimates of sorghum damage caused by ABC in protected and unprotected plots were spoiled by quelea attack. Although damage caused by the two pests can often be distinguished, under the present field conditions this could not be done reliably.

In conclusion, the findings of the present trials suggest that barrier spraying is effective against ABC and that it could potentially make a major contribution to the management of ABC outbreaks. A single barrier application of fipronil at a dose rate of 175 g-ai ha^{-1} resulted in a 65% reduction in the number of ABC present in plots subject to high invasion from neighbouring *Acacia* scrub, over a 2 week period. A subsequent study of the impact of this control method on non-target invertebrates suggested that this control method is relatively benign environmentally (see Output 4.3).

Summary of improved ABC management strategies outputs (Outputs 4).

- **ABC is considered the second most damaging crop pest in Central Region, just behind quelea.**
- **Farmers' knowledge of ABC was generally poor.**
- **None of the existing control measures were considered effective.**
- **There is widespread, passive acceptance that nothing can be done against ABC.**
- **Farmers expressed serious safety and environmental concerns.**
- **Surface application of baits was unacceptable.**
- **Use of trenches against ABC is more common in sandy soil areas.**
- **Farmers are willing to adopt the baited trench.**
- **Sorghum, maize and millet brans are equally acceptable as bait carriers.**
- **8 insecticides were tested at a range of concentrations for oral toxicity to ABC.**
- **Carbaryl/bran bait is recommended.**
- **A carbaryl/bran baited trench, depth 300mm, retained & killed 93% of ABC.**
- **Barrier spraying of fipronil (175 g-ai $ha^{-1)}$ resulted in 65% reduction in ABC.**
- **Baited trench and fipronil barrier spray effectively target ABC and appear to cause little environmental damage.**

- **A daily pattern of movement between habitat types was detected.**
- **Thermoregulation by basking is a prominent aspect of ABC behaviour.**
- **ABC invade crop fields at the time of panicle emergence.**
- **Dispersal patterns of males and females differ between sole and mixed crops.**

SETOTOJANE

ABC PROJECT

UK Department for International Development (DFID) Crop Protection Programme Project R7428:
"Biology and Control of Armoured Bush Crickets in Southern Africa"

Farmers' Demonstration Day, April 11th 2002, Shoshong, Botswana.

Most of the planning for the ABC demonstration/training day took place during January and February 2002. The idea of staging such an event was welcomed by the Department of Agricultural Research and by the Department of Forestry and Plant Production (which includes the extension service). The two departments worked side by side and cooperated to an unprecedented extent at local level to make this highly successful event possible.

Programme:

Welcome speeches + prayers

Songs relating to ABC performed by the Shoshong *Setotojane* choir

Drama - One farmer attempts to control an ABC outbreak (Shoshong Farmers' Group)

Demonstrations:
- ABC Biology (S Green)
- Why do we get ABC outbreaks? (P Mviha)
- ABC control methods (P Mosupi)

Speeches
- Local politician
- Representative of Minister of Agriculture
- Dr S V Green, ABC Project

ABC control poem, performed by local poet and assistant

Song of thanks by the Shoshong *Setotojane* choir

LUNCH

Return to ABC demonstrations to see dead ABC (baited trench and barrier spray)

Discussion and questionnaire-based interviews with 60 farmers.

END

The event was considered highly informative, enjoyable and well worthwhile by farmers, local organisers, and senior ministry personnel alike. In short, the day was a great success. The following night and next day it rained continuously.

The day's activities were filmed on video by the MoA, and songs were recorded, for use at future agricultural events.

Address by Dr S V Green to the *Setotojane* ABC Farmers' Demonstration Day, April 11th, 2002, Shoshong, Botswana.

Balalediwa ba ba tloltlegang, Balemi botlhe, Ke lo dumedisa ka pula!

I must first express my appreciation to the organisers and participants for coming to the *Setotojane* ABC Project farmers' day. I thank all the organisers here in Shoshong and in Mahalapye for your hard work and organisation which have made this day possible. I thank the farmers for travelling to Shoshong – some from far away – to attend this day and learn about *Setotojane*.

Botswana farmers are very familiar with *Setotojane*. When there is an outbreak, *Setotojane* is a very serious pest and does a lot of damage to farmers' crops here. In Shoshong farmers rated *Setotojane* the second most damaging pest, just after quelea birds. But maybe not all of you realise that Setotojane is a really serious pest in other countries as well. In Namibia, Angola, Zambia, and parts of Zimbabwe, South Africa, Mozambique, Malawi and Tanzania outbreaks of this pest cause many problems. Some of these countries are very poor indeed, and an outbreak of *Setotojane* can result in hunger and hardship for farmers and their families.

So you see, the research that the *Setotojane* ABC Project has conducted in Botswana, with excellent collaboration from the Ministry of Agriculture, is important because it will benefit the farmers in these other countries as well.

Two years ago the *Setotojane* ABC Project conducted a survey of farmers in eastern Botswana. This was a very important part of the project. It demonstrated to me just how important it is that researchers should talk to farmers directly and take note of their experiences and their views. I must admit we found that we had made some assumptions that were incorrect. I thought I was the expert on *Setotojane*, but it soon became clear that many of the farmers were experts too. For sharing your knowledge of *Setotojane* I thank you.

But another of the survey's findings caused us concern. We found that around half of the farmers that we interviewed thought that there was little or nothing that they could do to protect their crops from *Setotojane*.

Now, *Setotojane* is a formidable enemy for the farmer. He comes in thousands, he invades your fields, he eats your crops, he cannot be scared away. This is the nature of *Setotojane*.

But the most important message you should all take home from today's meeting is that YES you CAN defend your crops against this pest. There are actions you can take, that you have learnt about today, that WILL make a difference and WILL reduce the amount of crop damage caused by an outbreak of *Setotojane*. I hope that the next time there is an outbreak of *Setotojane* in Botswana – maybe next year or the year after – you will all use this new knowledge, the things you have learnt today, to defend your fields against *Setotojane*.

Re Ka Fenya *Setotojane*! Pula!