A review of insect infestation of maize in farm storage in Africa - with special reference to the ecology and control of *Prostephanus truncates* (NRI Bulletin 18)

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WITH SPECIAL REFERENCE TO THE ECOLOGY AND CONTROL OF *PROSTEPHANUS TRUNCATUS*

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ABBREVIATION

FAO Food and Agriculture Organization of the United Nations

Summaries

SUMMARY

African farmers operate traditional methods of integrated pest control when storing maize. They dry the maize well, store it on the cob in suitable structures and avoid protracted storage whenever possible. Such traditional methods are reasonably effective and studies have shown that under normal conditions they can keep losses down to less than 5% per year (Adams, 1977; Golob, 1981a and 1981b). Recent changes in farming systems have, however, interfered with traditional storage practices, resulting in the more frequent occurrence of serious losses. In particular, where high-yielding varieties of maize have been introduced, a dramatic increase in losses has often resulted. Other changes in farming systems have affected cropping patterns, causing farmers to store maize that is too wet, increasing its susceptibility to attack by insects and fungi.

The recent accidental introduction of the larger grain borer (*Prostephanus truncatus*) into Africa has added a new dimension to these problems, through its remarkable ability to damage well-dried maize, even when stored on the cob. This beetle is currently a more serious pest in parts of sub-Saharan Africa than in its native Central America, indicating that in Africa there are ecological, agricultural or socio-economic factors associated with maize storage which favour its success. Certainly, where *P. truncatus* has become established in Africa, it has commonly increased the loss levels sustained in traditional maize stores to a point at which intensified pest control by the farmer is an economic necessity (McFarlane, 1988).

There is thus a need to revise recommended methods for the control of insect pests of maize in farm storage, taking into account the changes which have reduced the effectiveness of traditional practices. This bulletin attempts to summarize available data from studies of pest infestation in traditional maize stores, relevant to current and future research in this field. The emphasis on *P. truncatus* in parts of the text reflects the importance currently attached to the development of integrated pest management strategies for this pest, in order to limit its spread in maize-producing regions of Africa.

RÉSUMÉ

Les agriculteurs africains ont recours à des méthodes traditionnelles de lutte intégrée contre les parasites lorsqu'ils entreposent leur maïs. Après l'avoir bien fait sécher, ils l'entreposent sur l'épi dans des installations appropriées en évitant, chaque fois que possible, un emmagasinage prolongé. De telles méthodes traditionnelles sont raisonnablement efficaces et les études ont démontré que, dans des conditions normales, les pertes peuvent être ainsi contenues au-dessous de 5% par an (Adams, 1977; Golob, 1981a et 1981b). De récents changements dans les systèmes d'exploitation sont venus toutefois déranger les pratiques traditionnelles d'entreposage et il en résulte que les pertes sérieuses sont désormais plus fréquentes. Un fait particulièrement notable est que l'introduction de variétés de maïs à haut rendement entraîne souvent une augmentation importante des pertes. D'autres changements dans les systèmes d'exploitation ont affecté les systèmes de culture, obligeant ainsi les agriculteurs à entreposer du maïs trop humide et par conséquent plus exposé aux insectes et aux champignons.

L'introduction récente en Afrique du térébrant *Prostephanus truncatus* a donné une nouvelle dimension à ces problèmes de par son aptitude remarquable à endommager le maïs bien séché, même lorsque celui-ci est entreposé sur l'épi. Ce parasite représente actuellement une menace plus sérieuse dans certaines régions de l'Afrique sub-saharienne qu'en Amérique Centrale d'où il est originaire, indiquant de ce fait que certains facteurs écologiques, agricoles ou socio-économiques liés à l'entreposage du maïs contribuent à la prolifération de ce parasite. Il est en tous cas certain que dans les régions d'Afrique où le *Prostephanus truncatus* s'est implanté, les pertes subies dans les entrepôts de maïs traditionnels ont atteint de tels niveaux qu'une lutte intensifiée contre les parasites s'impose désormais aux agriculteurs comme une nécessité économique (McFarlane, 1988).

Il s'avère donc nécessaire de revoir les méthodes préconisées pour la lutte contre les insectes nuisibles au maïs entreposé en tenant compte des changements qui ont diminué l'efficacité des pratiques traditionnelles. Le présent rapport s'efforce de dresser le bilan des données obtenues à partir des études sur les infestations par parasites dans les entrepôts de maïs traditionnels, et se rapportant aux travaux de recherche actuels et futurs dans ce domaine. L'intérêt attribué au *Prostephanus truncatus* dans certaines parties du texte reflète l'importance actuellement accordée à la mise au point de stratégies de lutte intégrée contre ce parasite en vue de limiter sa propagation dans les régions africaines productrices de maïs.

RESUMEN

Al realizar el almacenamiento del maíz, el agricultor africano utiliza métodos tradicionales de control integrado de plagas, secando bien el maíz, almacenándolo en la mazorca en estructuras apropiadas y evitando su mantenimiento prolongado en almacén, siempre que resulta posible. Estos métodos tradicionales son bastante eficaces, habiéndose establecido que, bajo condiciones normales, pueden reducir las pérdidas a menos del 5% anual (Adams, 1977; Golob, 1981a y 1981b). Valga apuntar, sin embargo que, los recientes cambios ocurridos en los sistemas agrícolas han interferido con los métodos tradicionales de almacenamiento, lo cual ha resultado en pérdidas más serias y frecuentes. De manera particular, en aquellos casos en que se ha llevado a cabo la introducción de variedades de maíz con elevado rendimiento, se ha producido, a menudo, un dramático aumento en las pérdidas. Otros cambios ocurridos en los sistemas agrícolas han afectado las técnicas de cultivo, lo cual ha hecho que el agricultor se haya visto obligado a almacenar maíz demasiado húmedo, con lo que se ha incrementado su susceptibilidad al ataque de los insectos y de los mohos.

La reciente introducción en Africa del escarabajo taladrador del maíz *Prostephanus truncatus* ha venido a incrementar los problemas, dada su extraordinaria capacidad para atacar maíz bien seco, aun cuando se halla almacenado en la mazorca. Este escarabajo está produciendo en la actualidad estragos más serios en el Africa Subsahariana que en los Países Centroamericanos de origen. Ellos nos lleva a concluir que existen en Africa factores ecológicos, agrícolas o socioeconómicos asociados con el almacenamiento del maíz, que favorecen su desarrollo. No cabe duda de que, en aquellos lugares de Africa en que el *P. truncatus* se ha establecido, las pérdidas resultantes en los almacenes tradicionales de maíz han ascendido a niveles tales, que hacen económicamente imprescindible la intensificación del control de plagas por parte del agricultor (McFarlane, 1988).

En consecuencia, se hace imperativa la revisión de los métodos recomendados para el control de las plagas del maíz en el almacenamiento en explotación, teniendo en cuenta los cambios que han reducido la eficiencia de los métodos tradicionales. El presente informe nos ofrece un resumen de los datos disponibles de estudios sobre infestación de plagas en almacenes de maíz, de interés para estudios de investigación actuales y futuros en este sector. El énfasis puesto sobre el *P. truncatus* en algunas partes del texto es un reflejo de la importancia hoy día asignada al desarrollo de estrategias integradas de gestión para esta plaga, con la mirada puesta en la reducción de su propagación por las regiones africanas dedicadas a la producción de maíz.

Life histories of the major pest species of stored maize

A large number of insect species infest stored maize in the tropics, and an even greater number can be found within maize cribs. The environmental conditions necessary for the development of most of these species are largely similar, but small differences in tolerances of temperature and humidity ranges may influence the success of a particular species in a particular environment. Detailed information is given here only for *Prostephanus truncatus, Sitophilus* spp., and *Sitotroga cerealella,* as these are currently the most important maize pests in Africa.

PROSTEPHANUS TRUNCATUS (Coleoptera: Bostrichidae)

Common name: larger grain borer

P. truncatus is an important pest of maize and dried cassava roots in Latin America and parts of sub-Saharan Africa. A number of commodities, such as groundnuts, cowpeas, coffee and cocoa are damaged by the tunnelling of the adults (Shires, 1977), but the beetle does not appear capable of breeding on these crops. The insect is apparently able to develop on cereals other than maize, such as soft varieties of wheat and sorghum, but serious losses in storage have so far been restricted to maize and cassava.

Various laboratory studies of the life history of *P. truncatus* have produced widely disparate measures of development parameters such as total egg production. This variation (reviewed in Hodges, 1986) probably reflects differences in aspects of experimental technique, such as the food substrate provided (*see* Appendix 1). The optimum conditions for development on maize are approximately 32°C and 70-80% relative humidity (r.h.). Under these conditions, the minimum development period recorded is 24-5 days on ground maize or whole maize grains.

The eggs are laid within maize grains, in tunnels created by the adults. Under optimum conditions, larvae hatch after an average of 4.1 days and the mean larval period is 16.1 days. There are normally three instars (Bell and Watters, 1982; Subramanyam *et al.*, 1985), one less than in the related bostrichid pest species *Rhyzopertha dominica.* The last instar larva of *P. truncatus* constructs a pupal case from frass stuck together with a larval secretion, either within the grain or surrounding dust. In contrast, *Dinoderus minutus,* another similar bostrichid which can infest stored maize, apparently pupates in an unlined cell excavated in a solid substrate. The pupae of *R. dominica* lie free in the food medium (Hodges, 1986). The mean pupal period for *P. truncatus* lasts 4.7 days under optimal conditions.

Humidity conditions in the range 50-80% r.h. do not appear to affect the beetles' development on maize flour greatly. In maize flour at 32°C and 40% r.h., development was completed in an average of 38 days, and mortality of immature stages was 40%. In Tanzania, heavy infestations of *P. truncatus* have been found on maize with a moisture content of 9-11% (equivalent to an ambient r.h. of 40-50%). The mean development periods on yellow 'American No. 3' maize and blocks of dried cassava, at 27°C and 70% r.h., were 39.2 days and 43.1 days respectively, suggesting that maize is more suitable for development of *P. truncatus* than cassava (Nyakunga, 1982).

When *P. truncatus* infests maize or cassava, the initial cause of weight loss is the conversion of the commodity into flour by adult tunnelling. At controlled temperatures of 25°C, 30°C and 35°C, 50 adults placed on 100 g of shelled maize, caused weight losses of 3.8%, 14.6% and 8.8%, respectively, in only 20 days (Subramanyam *et al.*, 1987). Cowley *et al.* (1980) observed that in a single generation experiment in which adults were placed on stabilized grains for 42 days, most of the damage was caused by the adults, which continued to bore through grain regardless of the amount of flour already present. Hodges (1986) considers that until a large population of larvae is established, feeding activity may be of secondary importance as a source of loss. In this respect *P. truncatus* may differ from other species, such as *S. zeamais*, in which larval feeding is responsible for the majority of the damage.

SITOPHILUS ZEAMAIS AND *SITOPHILUS ORYZAE* (Coleoptera: Curculionidae)

Common names: maize weevil and rice weevil

Both *Sitophilus zeamais* and *S. oryzae* are serious pests of stored cereals found throughout the tropics. In general, *S. zeamais* is more common on maize, and *S. oryzae* more frequently associated with small-grained cereals (Longstaff, 1981). However, there are many reports of the two species occurring together in African maize stores (Schulten, 1976). The adults of both species live for several months. Females lay up to 150 eggs, mostly in the first 4-5 weeks of adult life. Optimum conditions for development are 25-27°C and 70% r.h. The eggs are laid individually in small cavities chewed into the surface of the grain by the female and covered by a waxy secretion, which when hardened is usually referred to as an 'egg-plug'. Under optimal conditions larvae take 6-7 days to hatch and there are four larval instars. The total length of the larval and pupal stages are 18-22 days and 6-7 days, respectively. Pupation usually takes place within the grain. The newly developed adults chew their way out, leaving characteristic emergence holes. The total development period of *S. zeamais* under optimal conditions has been shown to vary from 31 to 37 days, depending on the variety of maize provided as food.

SITOTROGA CEREALELLA (Lepidoptera: Gelechiidae)

In some tropical areas, *S. cerealella* is regarded as the most serious pest of large-grained cereals. The adult moths live for 7-14 days. They mate soon after emergence and females may begin to lay eggs within 24 hours. The eggs are laid on cereal grains, either singly or in clumps of up to 200. At 30°C and 70% r.h. the eggs hatch after 3 days, on average. The first instar larvae bore into the grain, completing development within a single grain. Temperature limits for successful development are 16-35°C. Humidities of between 50% and 90% apparently have little effect on the development rate. At 30°C and 80% r.h., larval development is completed within 19 days. Before pupation, the larvae create chambers just underneath the surfaces of the grains, forming small circular 'windows' of translucent seed coat. After a pupal stage lasting approximately 5 days, the newly emerged adults push through the windows of the seed coats, leaving round holes. Under optimum conditions the complete life cycle takes about 28 days.

Because the adult moths are unable to penetrate densely packed grain, and the larvae are essentially immobile, infestation of shelled maize stocks is generally restricted to exposed surface layers. Thus, the importance of *S. cerealella* as a pest of stored maize can be reduced by storing shelled grains rather than maize cobs.

Pre-harvest infestation of maize by storage pests

A number of insect species regarded principally as post-harvest pests are able to infest maize cobs in the field as the crop approaches maturity. While there is a considerable amount of information on the occurrence of *Sitophilus zeamais* in growing maize crops, the literature on field infestation of maize by other post-harvest pests is much less extensive. *Prostephanus truncatus* has been recorded as infesting maize in the field in Central America (Giles, 1975; Boeye *et al.*, unpublished) and in Tanzania (Dendy, personal communication). In 1982, a survey in Moshi, Tanzania, revealed that 5% of cobs in fields near government flour mills were infested with *P. truncatus* at the time of harvest (Mushi, 1984). Adult beetles have also been found in the stems of maize plants left standing in the field after harvest in southern Tanzania (Golob, personal communication). There is, however, no detailed information on the timing of initial infestation or on the sources of the insects present in the growing crop. The other bostrichids which are considered minor pests of stored maize, *Rhyzopertha dominica* and *Dinoderus* spp., are apparently of little importance in the field (Schulten, 1976).

Sitotroga cerealella can infest maize before harvest. This species was found to be more common in the field than *Sitophilus* spp., both in Kenya and Malawi (de Lima, 1979; Dobie, 1974). However, Markham (1981) did not find *S. cerealella* present in the field during either the wet-season or the dry-season harvest in south-west Nigeria.

FACTORS AFFECTING PRE-HARVEST INFESTATION

Maturity of maize grains

The ability of *S. zeamais* and other 'post-harvest' pests to infest growing maize plants appears to be influenced by factors related to the maturity of the grains. In Kenya, Giles and Ashman (1971), artificially pollinated maize plants of several varieties, covered the developing ears with cloth bags, and then introduced marked adult *S. zeamais* into the bags at different times after pollination. The bags were left in place until the cobs were ready for harvesting, at which time survival of marked adults and the presence or absence of F1 generation adults were recorded. The earliest introduction of adults which resulted in their survival until harvest was 25 days after pollination. The earliest introduction which allowed F1 individuals to complete development was 50 days after pollination. The same technique was used to confine adult weevils on maize ears for 5-day periods, at different times after pollination. Again the first F1 generation adults developed from eggs laid 45-50 days after pollination. At this stage the mean development period of F1 individuals was 70 days, but the development period decreased as the maize crop matured.

One of the most important factors which changes with maturation of the grain is moisture content (*see* Appendix 2). This decreases as the crop approaches maturity and is generally 30% or less, at harvest. Some secondary pests such as *Cathartus quadricollis* and *Carpophilus* spp. can act as primary pests early in the growing season, when the maize has a high moisture content

(Schulten, 1976). However, as the moisture content drops towards the end of the growing season, only damaged grains remain susceptible to attack by these species. Their distribution at harvest time is thus likely to be highly clumped, with large numbers occurring only in those cobs already infested by primary pest species or damaged in some other way.

In south-west Nigeria, Markham (1981) examined cobs from a field of maize 3 weeks before the dry-season harvest (late November). He found no evidence of *S. zeamais* infestation of the grains, which had a mean moisture content of 57%. Three weeks later, 45% of the harvested cobs were infested by *S. zeamais*; the moisture content of the grains had by then dropped to 30%. At the wet-season harvest, mean grain moisture content was again 30%. However, only 28% of the cobs were infested. Obviously, a number of other factors were operating to influence the level of field infestation.

Dix and All (1985) suggested that immature maize at a high-moisture content lacks certain chemical compounds attractive to weevils, which are produced by maturing grains. Thus, although *Sitophilus* spp. appear only to infest grain once the moisture content has dropped to a certain level, it may be some other aspect of grain maturity which is critical in determining the timing of infestation in the field.

Husk cover

Another important factor affecting pre-harvest infestation of maize by storage species is the degree to which the maize grains are exposed because of incomplete husk cover. There is extensive literature from the United States on the increased susceptibility to attack by *Sitophilus* spp. of new maize cultivars which produce large ears, but which have poor husk cover (Schulten, 1976). In Kenya, Giles and Ashman (1971) examined maize ears 2 months before harvest. On average, 7% were infested with *S. zeamais*. When the cobs were then divided into categories depending on the degree of protection afforded by the husk, only 1% of the cobs with complete husk cover were infested, whereas 20% of those in which grain could be observed at the tip were infested. Exposing cobs by opening the sheaths at the tip greatly increased the numbers of weevils caught in a suction trap placed in a maize field (Taylor, 1971). Taylor concluded that exposed ears induced flight activity of *Sitophilus* spp. and thus increased the probability that cobs with short husks would become infested.

Just as those cobs with incomplete husk cover are more susceptible to infestation by *S. zeamais*, so weevil infestation appears to be aided by damage to the sheath and grains caused by field pests. In south-west Nigeria, Cornes (1964) recorded a succession in pre-harvest infestation of maize crops. The silks were damaged by dipteran spp. and by the common moth pest, *Heliothis armigera* (Noctuidae). Later in the development of the crop, the tips of the ears were damaged by moths of the genera *Mussidia* (Phycitidae) and *Argyroploce* (Olethreutidae). Finally, the damaged cob apices and sheaths were invaded by *S. zeamais* and other storage species. In the same region of Nigeria, Markham (1981) found *Eldana saccharina* (Noctuidae) and *Mussidia nigrivenella* to be the main cause of insect damage to the sheaths. The latter species causes similar damage to maize plants in Ghana (Rawnsley, 1969).

Bird damage to husks also increases the susceptibility of cobs in the field to attack by storage species. In experiments in southern United States, protecting maize plants from bird attack reduced the number of ears which were damaged by *Sitophilus* spp. by two-thirds (Floyd and Powell, 1958). When the crop was protected from both birds and the larvae of the main lepidopteran pest, *Pyroderces rileyi* (by removing the silks) weevil damage was reduced by 78%, in comparison with unprotected plots.

Dispersal behaviour and flight activity of *Sitophilus* spp.

A pre-harvest infestation of maize by *S. zeamais* appears to be unevenly distributed within a field. Dix and All (1985) carried out intensive sampling of maize fields and reported a clumped distribution both of the weevil population and of weevil-infested ears. They suggest that clumping is a response to the release of aggregation pheromone by the first males to colonize the maize plants (there was a male-to-female ratio of 1.6: 1.0 in the weevil populations collected from cobs sampled 2 months before harvest). In most of the fields studied, the weevil-infested ears were distributed in a linear pattern across the field. This may again have resulted from down-wind dispersal of aggregation pheromone from colonizing males.

A marked 'edge of field' effect has been noted in some studies of field infestation of *Sitophilus* spp.; numbers of adult weevils drop dramatically 15-30 m from the field border (Kirk, 1965; Blickenstaff, 1960; Giles and Ashman, 1971). Surveys of a number of fields indicated that, even at the margins, the distribution of insects was uneven and was generally determined by the direction and proximity of infested maize stores to the growing crop. This suggests that infested stores are the main source of field populations and that the dispersal behaviour of *Sitophilus* from infested stores is one of the main factors in determining the extent of pre-harvest infestation of maize.

Chesnut (1972) studied the dispersal of *S. zeamais* from a source of infestation using adults marked with a fine paint spray. No marked adults were found on cobs located more than 400 m from the release point. Giles (1969) also used adults with a paint mark on the pronotum to study the flight range of *S. zeamais* adults in Kenya. No marked adults were caught in a suction trap, 100 m from the release point. A plywood screen sticky trap (5 × 2 m) placed on the edge of a maize field less than 400 m from an infested store trapped only 11 weevils in 2 months. Kirk's (1965) experiments with sticky traps placed at different elevations between ground level and a height of 20 m, showed that screens at or below the tops of the maize plants caught larger numbers of *Sitophilus* than higher traps. From this and other studies Kirk concluded that the insects were low flying, with a limited flight range, and that once they reached a suitable environment, such as a field of maize approaching maturity, they were unlikely to disperse further.

Taylor (1971) and Giles (1969) used suction traps to examine the flight activity of *S. zeamais* in the field. Both authors recorded a peak of flight activity in the afternoon, indicating a difference in the pattern of activity between populations of this species in the field and in stores (where flight activity peaks at dusk).

EFFECT OF GRAIN DRYING ON INFESTATION LEVELS

When maize reaches physiological maturity the grain has a moisture content of 30-35% (FAO, 1975). If harvested and stored without further drying, rapid deterioration is likely, as a result of mould growth and insect attack. In hot dry areas, such as western Tanzania and the northern savannah areas of West Africa, maize left standing in the field will dry within days to a safe moisture content for storage (< 14%). In more humid areas, maize left standing in the field may take weeks to dry, and during this time losses resulting from bird, rodent and insect attack may be considerable.

In some regions of Central America, maize is left to dry in the field for weeks or months after reaching maturity (Hoppe, 1986). The stems are first bent over just below the lower ear; a practice which is believed to accelerate drying and reduce insect damage to the cobs. In Nicaragua, Giles (1975) examined the effect of 'doubling' the maize plants in this way, approximately 60 days after anthesis. Although this action did not increase the rate of drying over a period of 7 weeks, the numbers of *Sitophilus* spp., *P. truncatus*, *Cathartus quadricollis* and *Gnatocerus maxillosus* infesting the 'doubled' heads were reduced in comparison with plants left erect.

Markham (1981) examined the effect of delaying the harvest on the levels of infestation in cribs in south-west Nigeria. Half the cobs in a field were harvested when the crop was considered ready, the remaining cobs being left in the field for an additional 3 weeks. When these late-harvested cobs were examined before storage, they contained significantly fewer numbers of *S. zeamais* than the cobs from the early harvest that had already been in store for 3 weeks. Thus the build-up of pest populations appeared to be delayed by harvesting later. However, when cobs from the first and second harvesting dates were examined, 1 month after the late-harvested cobs had been placed in store, there was no longer any significant difference in the level of infestation.

In the southern United States, Keever *et al.* (1987) conducted studies to determine the effect of mechanically threshing and drying maize infested in the field by *S. zeamais*. Sixty small field plots were planted using one of three hybrids. Half the plots were then artificially infested with *S. zeamais*, by placing 10 unsexed adults in a muslin bag over the top ear of each plant 25 days after full silking. Samples were removed for examination at several different stages in the harvesting process: immediately before harvest; immediately after threshing; after drying; and after 6 and 12 weeks in storage. The numbers of insects from the cobs in the field samples were not related to the numbers in the threshed grains from the same plot, but this may simply reflect the different technique required to determine insect numbers on maize cobs and on shelled grain. On average, threshing removed approximately 15% of the field population from the maize, but left many live weevils in the chaff, which were able to disperse in search of new food sources. Efficient drying reduced the remaining populations by 88% and appeared to cause mortality of the insects.

Where field drying is ineffective or impracticable, maize cobs are generally hung above a cooking fire to dry, or spread out on racks or mats in direct sunlight. The drying process can be continued by storing the cobs either in a 'crib' (the name given to a variety of traditional crop storage structures which are essentially open-sided) or in the roof space of farm houses. Maize crib design varies considerably, as does the method of loading cobs into the cribs; this may involve a random arrangement of cobs or tight packing in a particular pattern. Even in relatively small cribs or storage spaces, there may be a considerable variation in environmental parameters such as air flow, between different parts of the store. Thus the moisture content of the grain may vary within the crib and this in turn may influence the distribution of insects and losses. Recently, a considerable research effort has gone into the design of maize cribs which exploit the drying capabilities of natural air movement and which reduce the suitability of the storage environment for insect population development (FAO, 1980 and 1985).

EFFECT OF PRE-HARVEST INFESTATION ON INSECT POPULATION AND LOSS LEVELS DURING STORAGE

There are few reports of experiments aimed at determining the effect of pre-harvest infestation on the subsequent build up of storage pest populations. Floyd (1971) examined the relationship between initial levels of grain damage at time of storage and subsequent development of *S. zeamais* populations on shelled grains. Maize samples with different percentages of damaged grain (1.0%, 1.2%, 2.4%, 3.6%, and 8.0% of the grains containing larval channels and/or adult emergence holes) were kept in separate, open, plywood bins in a warehouse in the southern United States. The warehouse contained maize from a previous crop, heavily infested with *S. zeamais* and *S. cerealella*, which was expected to provide a source of infestation during the experiment. At monthly intervals over a storage period of 1 year, the numbers of adult weevils and the percentage of damaged grains in 'spear' samples from the different bins were recorded. Throughout the 12 months, the numbers of adult weevils and the percentage of damaged grains in the samples were positively correlated with the initial levels of infestation in the grain.

In Kenya, Giles and Ashman (1971) harvested, dehusked and stored in separate cribs, maize cobs from two fields with different mean levels of pre-harvest infestation by *S. zeamais* (0.8% and 3.2% of insect-damaged grain). Subsequently, at 8-week intervals, cobs were removed and the numbers of adult weevils and the percentage of damaged grain were counted. The insect population initially developed much faster in the maize with the higher level of pre-harvest infestation and after 6 months in storage the percentage of damaged grain was three times greater in the samples with the higher level of field infestation. However, the difference in *S. zeamais* populations was much less marked after 8 months in storage. By this time, the percentage of damaged grains was approximately equal.

Pointel (1969) derived a positive correlation between the level of damage to the cobs caused by moth larvae while the crop was drying in the field and weevil infestation of stored maize in Togo. In Nigeria, Markham (1981) studied the effects of pre-harvest damage by lepidopteran field pests on the rate of development of storage pests attacking dehusked cobs stored in an experimental crib. Cobs were separated at harvest into three categories – undamaged, partially damaged and heavily damaged; heavily damaged cobs were then discarded altogether, in accordance with local farming procedure. The remaining cobs were placed into a number of coarse mesh bags, keeping the damaged and the undamaged cobs apart. The bags were then held in an experimental maize crib for 4 months. The numbers of *S. zeamais* adults and their hymenopteran parasitoids (included in order that the numbers of the host species should not be underestimated) were much higher on damaged cobs throughout the storage period. However, emergence of adult *S. zeamais* from the sampled cobs in the week after each sample collection (an indication of the level of recruitment to the next generation) did not show any significant difference between the two categories of cobs. Nor was there any difference in weight loss of grains from the sampled cobs.

Markham concluded that although field damage to cobs leads to higher populations of *S. zeamais* at harvest and is important for a considerable period in maintaining high populations of secondary pest species, it has little long-term effect on the numbers of primary pests, or on weight loss, when maize is stored for 6 months or more. Thus, while for short storage periods, isolation of cobs with obvious damage or infestation at harvest may benefit the farmer by delaying the build up of pest populations, removing infested cobs at harvest time will be of less benefit over longer storage periods. This was confirmed by experiments in which grain fumigated at harvest became as heavily infested with *S. zeamais* as untreated material in nearby cribs, within a few months in storage (Markham, 1981). Whether these conclusions are also relevant to *P. truncatus*, which may show different characteristics as a field-to-storage pest, requires verification.

Measurement of losses to stored maize

SAMPLING FROM MAIZE STORES

In any attempt to assess weight loss or insect distribution within a maize crib the sampling technique used will depend on the objectives of the study and the number of samples which can be taken from the stores involved. If the actual losses faced by the farm household over a storage season are being determined by a regular programme of 'on-farm' sampling, then at each visit samples should be collected from the maize that will be removed for consumption before the next sampling occasion; generally the maize nearest the point of access into the store. The losses recorded on each sampling occasion, used in conjunction with records of the quantity of maize removed for consumption between visits to the store, will provide an accurate measure of weight loss over a storage season.

This type of sampling will produce inaccurate results, however, if the values obtained from one set of samples are extrapolated to provide a measure of total losses from the crib at a particular point in time. Insect populations and damage levels are not evenly distributed within a maize crib; they are often concentrated in the outer layers of maize, particularly on the upper surface of the crib (Kockum, 1953; Pointel, 1969; Markham, 1981). Thus to obtain an accurate measure of total losses from a single visit to a store, a sampling method must be used which ensures that every cob or grain within the store has an equal chance of selection.

There is at present no satisfactory method of removing samples from within cob stores without removing whole cobs. When cobs are packed tightly, removing an individual cob from more than 30 cm below the surface will cause considerable disruption to the stacking of other cobs, with a resulting effect on the distribution of both cobs and insects within the store. One solution to the problem of inaccessability is to empty the crib completely when samples are collected. This kind of 'destructive' sampling has three advantages: sampling can be carried out in a precisely defined, stratified, random manner; large samples can be taken, as depletion of the sampling universe is not a problem; samples will be truly representative in that they will have remained undisturbed until the time of sampling.

Destructive sampling was used by de Lima (1979) to obtain representative samples from maize cob stores in Kenya. In order to collect ten completely representative cobs from randomly selected stores, each of the chosen stores was emptied one cob at a time, and all the cobs were numbered. Ten cobs were then selected using random numbers. Because of the resulting disturbance of both cobs and insects, stores were examined only once in each storage season. This was not a problem in itself because the large numbers of stores included in the survey meant that destructive sampling did not significantly restrict the choice of stores on later sampling dates. However, if a loss assessment exercise is carried out at a limited number of sites, for example, using experimental cribs or stores on a field station, then there are unlikely to be sufficient stores available to carry out destructive sampling at regular intervals during a storage season.

Unloading a store inevitably causes considerable disturbance to cobs and insects. When cobs in storage are jolted or exposed to direct sunlight for more than a few seconds, a large percentage of the insects present will leave the cob (Markham, 1981). This response caused a marked increase in insect counts in neighbouring cribs close to the one being unloaded, even when rapid-knock-down pyrethroids were used to minimize cross-infestation. Attempting to refill a store by replacing the cobs in their original position is time consuming and is unlikely to recreate the distribution of insects present in the store before sampling. The distribution of losses within the store will be similarly effected by undue disturbance.

As mobile insect stages can disperse when disturbed before sample cobs can be isolated, the most reliable estimates of insect population density are based on the collection of the immature stages of species which develop entirely within the commodity. For species such as *Sitophilus zeamais*, in which larval feeding is the main cause of weight loss, this type of sampling may allow an accurate relationship to be determined between the numbers of insects (larvae) and the weight loss. However, it may be impossible to relate larval numbers to weight loss for *Prostephanus truncatus*, as the adults are initially responsible for much of the damage. The main disadvantage with counting immature stages is the increased amount of time needed to dissect the grains in order to obtain accurate results.

In his studies of maize crib insect ecology, Markham (1981) adopted a technique which he called 'partially destructive' or 'replacement' sampling. Alterations were made to a crib, constructed to an improved FAO design (FAO, 1980), to allow the removal and replacement of cobs from the interior of the maize bulk, without disturbing the surrounding cobs. This was done by creating both horizontal and vertical wire-mesh partitions within the crib. Individual cobs were marked with an indelible ink code, indicating both their compartment and their position within it. At loading, care was taken to ensure that cobs were stacked closely against the partitions so that the grain bulk was effectively continuous. Cobs removed from the experimental crib on sampling dates were replaced immediately with cobs from the same position in an identical crib, filled with maize from the same harvest. Some compartments in the crib were deliberately excluded from the sampling regime, to provide an undisturbed reservoir of insects from which reinfestation of cobs could occur.

In experiments to test insecticide efficiency, Golob *et al.* (1985) used a sampling method similar to, but less sophisticated than Markham's. Treated cobs were placed in an experimental crib divided into small compartments using wire netting. Each of the different treatments was replicated 20 times, with 60 cobs in each replicate. Replicates were placed in separate compartments and all the replicates of a particular treatment were aggregated in a single block, the position of which within the crib was chosen at random. At 8-week intervals, 4 complete replicates were removed from each treatment block. Although this experimental layout was not intended to recreate the conditions in a traditional maize store, it could be adapted for this purpose. One potential problem with this sampling procedure for the study of insect or loss distribution within cribs, is the removal of all the cobs from a compartment on a particular occasion. This creates spaces within the crib which could restrict the movement of insects through the bulk of the maize and thus affect their eventual distribution.

A similar method was used by Ayertey (1984) to test the efficiency of insecticides for the protection of maize in cribs in southern Nigeria. Fourteen cribs each with 8 wire compartments were filled with dehusked maize cobs. Six different insecticide dust treatments were applied, each to 2 cribs, leaving 2 treated only with blank talc as controls. At 8-week sampling intervals, all the cobs in 2 compartments (chosen at random) of each crib were carefully unloaded and a number of cobs collected for analysis. While the compartments of a crib were being unloaded, a sheet of cloth was placed under the crib and any insects or grains which fell onto the cloth were collected.

SAMPLE SIZE

In theory, the amount of grain removed from a store on any one sampling occasion should be proportional to the amount of grain in the store, the range of loss measurements expected and the desired precision of the loss measurements (Harris and Lindblad, 1978). In a number of practical loss assessment studies where maize stores were sampled at regular intervals and patterns of consumption recorded, 10 cobs (or the equivalent weight of shelled grain) were removed as the standard sample size (Schulten, 1972; Adams, 1977; Golob, 1981a; 1981b). This provided a sufficient amount of grain for use in standard loss assessment procedures and is considered large enough to provide a reasonably accurate indication of the loss in that portion of the maize which is consumed between sampling dates. However, when loss assessments must be derived from only one or two visits during the storage season and samples must be representative of all the maize in store, a larger sample size is needed to provide a reliable measurement of overall loss.

Markham (1981) found that the insect infestation levels of individual cobs varied markedly, even when cobs from the same compartment of an experimental crib were compared. When using destructive sampling regimes to determine accurately the distribution of insect populations and weight loss within cribs containing 0.5 tonnes of maize cobs, it was necessary to remove groups of 5 cobs from up to 24 different positions within the crib. Other experiments, in which replacement sampling was used, required the removal of similar numbers of cobs from a crib on several sampling occasions. In this type of study, there is an obvious risk that the removal of large numbers of cobs and their replacement with cobs which may be infested to a much greater or lesser extent, will itself significantly alter the pest populations in the crib, with a resulting effect on loss measurements.

Whether sampling from farm stores or experimental cribs, large sample sizes create a problem by increasing the amount of labour and time required for analysis. This is particularly important when insect numbers are being considered, as well as loss levels. Delays in analysis of comparable samples can create apparent changes in numbers of insects present, for example, as a result of the sudden emergence of adults from pupation. The problem of analysis time prevented Markham (1981) from investigating simultaneously, both short-term changes in insect distribution within the crib and changes in population density over a storage season. To assess both parameters accurately, within a single experiment, would have required frequent, large-scale sampling with prohibitively long analysis times.

The variability in the loss levels among cobs recorded by Markham (1981) was largely a result of the tendency of *S. zeamais* (the most numerous pest present) to remain within the cob it initially infests until food and oviposition sites become seriously depleted. Thus, the behaviour of the insect has important implications for the number of samples which will be required in order to obtain sufficiently accurate loss measurements. If *P. truncatus* behaves differently in this respect, then sampling methods which have proved acceptable for loss assessment studies in the past may not provide accurate data when *P. truncatus* is the most numerous pest in maize stores. For this reason the statistical basis for sampling maize cobs in farmers' stores, in order both to detect *P. truncatus* and to assess accurately the losses caused by infestation, should be defined.

STANDARD LOSS ASSESSMENT METHODOLOGY

The methods generally used to assess the losses caused by insects to stored grain tend to ignore qualitative loss and concentrate upon direct loss of weight caused by insect feeding. To this extent they do not reflect the consumers' view of loss. A farmer may consider maize to be unfit for human consumption when the actual weight loss caused by insects is only 10-20%, particularly if insect infestation has also encouraged the growth of mould on the maize. Thus, although the farmer may be able to use the damaged grains as animal feed, in both economic and nutritional terms his loss is greater than 10-20% of the value of the maize. A considerable amount of additional information is necessary if figures for quantitative weight loss are to be converted into a measure of loss which is relevant to the farmer. Nevertheless, an accurate measure of the weight loss frequently provides the most reliable basis from which to calculate other measures of loss.

Four methods of quantitative loss assessment have gained widespread acceptance (Harris and Lindblad, 1978; Boxall, 1986). Those methods which are based on the comparison of sample or sub-sample weights, require that the necessary calculations are carried out using the dry weight of grain in the sample. This, in turn, requires that the wet weight of the grain and its moisture content be determined first (*see* Appendix 3).

Standard volume/weight, volumetric or bulk density method. This method is based on the principle that losses can be measured by comparing the weight of a standard volume of grain from a working sample*, with the known weight of the same volume of undamaged grain. As the weight of grain occupying a fixed volume is affected by its moisture content, the relationship between the moisture content and the weight of grain must be determined at the start of the experiment using samples of undamaged grain. Graphing this relationship then allows the weight of grain from a working sample with a particular moisture content, to be compared with the baseline value for undamaged grain at the same moisture content. This method only remains accurate until the levels of damage to working samples become such that the packing of grains into the standard volume is affected.

Gravimetric or count-and-weigh method. This method is often used in situations where no baseline samples can be collected at the beginning of a storage period. It requires that each working sample be divided into damaged and undamaged portions. The number of grains in each portion and the total weights of damaged and undamaged grains are then determined. These values are used to compute the weight loss.

Converted percentage damage method. This method is based on the assumption that the actual level of weight loss can be estimated from the percentage of damaged grains in a working sample, once the relationship between damage and loss has been determined in the laboratory. While this is not necessarily true, this method may be useful when a large number of samples have to be analysed quickly or where losses have to be estimated in areas remote from laboratory facilities. The conversion factor can be made more reliable if the amount of damage to individual grains can be graded (for example, by counting the number of adult bruchid beetle emergence holes in legume seeds) and a conversion factor calculated for each level of damage.

Thousand grain mass (TGM) method. This method overcomes some of the problems encountered with the 'volumetric' and 'count-and -weigh' methods. It involves determination of the number and total weight of the grains in the sample. The mean grain weight is then calculated and multiplied by 1000. A reference TGM must be determined at the beginning of the storage season and loss measures obtained by comparison with the TGMs of working samples. Where grain size within a sample is highly variable, the reliability of this method will be improved by separating the grains into size classes and calculating a separate TGM for each size class (Proctor and Rowley, 1983).

These methods of assessing weight loss all have a similar basis, in that they use individual grains as the basic sample unit and rely on the assumption that grains damaged by insects will weigh less than undamaged grains. Because

*Working sample=a sample of grain collected from one of the stores included in the survey during the course of the loss assessment exercise.

of this, these methods have at least one common source of error – hidden infestation of grains by larvae, pupae or adult insects will tend to mask actual weight loss.

When assessing losses caused by *P. truncatus* in maize stores in Togo, Pantenius (1988) found cobs which were damaged to such an extent that the number of grains which had been present initially on the undamaged cob could not be determined. As the standard loss assessment methods cannot allow for missing grains, their use would have resulted in an underestimate of losses (Boxall, 1986). To avoid this, Pantenius based his loss measurements on a comparison between the mean total weight of grain on undamaged cobs at the beginning of the experiment, and the mean total weight of grain on cobs removed from storage at monthly intervals.

Markham (1981) also found problems in using standard loss assessment procedures for detailed studies of insect and loss distribution within experimental maize cribs. Methods based on weighing standard volumes or counting and weighing large numbers of grains were found to require too much time or sampled material in order to achieve sufficient precision. Instead, individual cobs were marked and weighed at harvest, and then reweighed at intervals during the storage season. When the cribs were finally unloaded the cobs were again weighed and then shelled. As the core had suffered no visible insect damage, the final dry weight of the core was subtracted from the initial dry weight of the cob. The final dry weight of sieved grain was then compared with the initial dry weight of grain and the difference taken as the loss during storage.

ESTIMATES OF LOSSES FROM MAIZE IN FARM STORES AND EXPERIMENTAL CRIBS

A number of attempts have been made, using the accepted methods described above, to estimate the extent of losses caused by insects to maize stored in a traditional manner by small-scale farmers (*see* Appendix 4). Adams (1977) examined losses sustained by maize in farm stores in Zambia by removing cobs at regular intervals and relating losses to patterns of consumption between sampling dates. The recorded losses of 2-6% were largely attributable to infestation by *S. zeamais*, *Sitotroga cerealella* and *Tribolium castaneum*. In parallel trials, using improved local stores constructed on a field station, shelled grain admixed with insecticidal dust suffered losses of only 1.1%.

Samples of maize cobs taken from farmers' stores in Kenya 9 months after harvest had sustained on average 1.6% and 1.3% weight loss as a result of infestation by *S. zeamais* and *S. cerealella*, respectively (de Lima, 1979). Provincial annual losses to stored maize due to insect attack were also calculated by de Lima and on average were 1-2% higher than this total. Maximum losses sustained by maize, stored for up to 10 months in central and southern Malawi, were 1.5% and 3% respectively (Golob, 1981a; 1981b). Golob concluded that the low level of loss demonstrated the suitability of traditional crop varieties and local methods of storage for the limitation of post-harvest loss in this region of Africa.

If these results are accepted as indicative of the loss levels which typically occur in East Africa, then it is apparent that *P. truncatus* is capable of causing mean levels of loss, over a storage period of 6-8 months, which are at least 5% higher than those caused by the indigenous African pest complex. A survey of farmers' stores in the area of the initial outbreak (Tabora, Tanzania) revealed that cobs damaged by *P. truncatus* had sustained an average loss of approximately 9%. In extreme cases 70-80% of the grains were damaged and the maize was unfit for human consumption (Golob and Hodges, 1982).

Most measurements of weight loss caused by *P. truncatus* have come from experiments essentially designed to determine the efficacy of insecticides against the pest complex on stored maize. In Tabora, Golob *et al.* (1983)

tested a range of insecticides on shelled grain against natural infestation by the pest complex, which was dominated by *P. truncatus*. After 18 weeks in an experimental crib, untreated control replicates had suffered 7-9% weight loss. The losses were attributable almost entirely to infestation by *P. truncatus*. *S. zeamais* was present at a much lower level and *S. cerealella*, *T. castaneum* and *Cryptolestes* spp. were present, but at such low densities as to be of negligible importance in contributing to overall weight loss.

In further trials using the same experimental crib, both shelled grain and cobs were treated with insecticide and stored for 10 months. After 8 months, weight loss to the untreated control cobs was approximately 27% (Golob *et al.*, 1985). At this stage the cobs were infested, almost exclusively, by *P. truncatus*. After 10 months the weight loss had reached 43%, by which time numbers of *S. zeamais* had increased to about the same level as *P. truncatus*. On shelled grain stored in the same crib, *S. zeamais* was the predominant species. The loose grains had sustained a loss of 15% after 8 months and 32% after 10 months.

Pantenius (1988) surveyed losses in Togo, both before and after *P. truncatus* became endemic in that country. The survey included comparisons of different store types; large round cribs built on low platforms; higher platforms under which a fire could be lit to improve drying; and storage space above the cooking fire inside the house. In addition, traditional varieties were compared with new, high-yielding hybrid cultivars. At the end of two storage seasons of 6 months and 4 months, when only the indigenous pest complex was present, the overall mean losses from all the stores included in the survey, were 7.7% and 6.4% respectively. After the longer storage period, losses in hybrid granaries averaged 12.5%, whereas local varieties had suffered only 2.5% loss. Cobs stored above cooking fires within houses had suffered significantly less damage than samples taken from the other types of store. Pantenius attributed this to the low moisture content of the cobs stored above the fire. After 6 and 8 months in stores where *P. truncatus* was present, mean losses were 30.2% and 44.8%, respectively. Unfortunately, Pantenius provided only overall mean results from this part of the survey and does not differentiate between types of store, or maize varieties. It is, therefore, impossible to determine whether traditional varieties were less susceptible to attack by *P. truncatus* than new hybrids, or whether different storage techniques had any significant influence on losses.

Markham (1981) recorded losses after 7 months, which varied from 30% to 45% in different parts of an experimental crib. These losses are much higher than those recorded in areas of East Africa which have essentially the same pest complex as south-west Nigeria (that is, *P. truncatus* is not present). In the second half of the storage period, losses were significantly higher on the surface of the crib than in the interior, and this was particularly true of the uppermost layer of cobs. The distribution of losses in the crib reflects the distribution of the *S. zeamais* population which tended to concentrate in the surface layers as the storage season progressed.

Physical constraints on pest population development

In Tanzania and in parts of Togo, maize cobs are frequently stored with their sheaths intact in the roof space of a house, where they are subjected to heat from the cooking fire beneath, or on platforms or racks in direct sunlight. Storage in this manner reduces the moisture content of the maize and appears to be largely effective in minimizing infestation by most common storage pests (Golob and Hodges, 1982; Pantenius, in press). However, both laboratory research (Hodges and Meik, 1984) and field studies (Hodges *et al.,* 1983a) have demonstrated that *Prostephanus truncatus* is tolerant of hot, dry environments and can survive on maize with a moisture content of below 10%. Thus, the beneficial effect of drying the maize thoroughly has been diminished in African regions where the larger grain borer is now endemic.

Research has also demonstrated that *P. truncatus,* is in general, a more serious pest of maize on the cob than of shelled grains (Golob, 1984). In laboratory experiments, Cowley *et al.* (1980) demonstrated that on simulated maize cobs (grains set in cellulose filler coated onto wooden blocks) *P. truncatus* caused much more damage than on loose maize, whereas the reverse was true for *Rhyzopertha dominica*, *Sitophilus zeamais* and *Tribolium castaneum*. Field trials in Tanzania conducted using an experimental crib also showed that most of the damage to the cobs was caused by *P. truncatus,* whereas the loose grains were almost exclusively infested by *S. zeamais* (Golob *et al.,* 1985). These results presumably reflect a greater capability of *P. truncatus* to attack maize grains which are stabilized in some way, as they are while still on the cob.

Shelling maize does not in itself offer complete protection from *P. truncatus.* In the Taveta region of southern Kenya, shelled maize stored in gunny bags in farm houses was damaged heavily by the pest (Muhihu and Kibata, 1985). Shelled grains held in large sacks thus appear to be sufficiently stabilized by the pressure from the surrounding grains to create more favourable conditions for the development of *P. truncatus* infestations. This conclusion is supported by results of an experiment in which shelled grains at the bottom of 90 kg sacks were more heavily damaged by *P. truncatus* than grains at the top of the sacks, which were presumably less stable (Golob, unpublished).

Golob *et al.* (1985) have shown that while storing shelled grain rather than maize cobs reduces losses to *P. truncatus,* the susceptibility of the maize to attack by *S. zeamais* and *Sitotroga cerealella* is increased by shelling. Because of this, farmers who were advised to shell their maize to combat *P. truncatus* are also advised to admix insecticidal dust with the grain to prevent excessive damage by other pests.

As previously stated, the intact husk on a cob forms a partial barrier to insects seeking to infest maize grains in the field. Markham (1981) examined the effect of removing the husk before storage, on the build-up of pest populations in maize cribs in south-west Nigeria. Retention of the husk after harvest did not appear to have any protective role against infestation by the pest species present. In fact by the end of the experiment, cobs with husks intact had a higher mean level of *S. zeamais* infestation than cobs without their sheaths, although the infestation was less evenly distributed. This probably reflects the tendency of maize pests, including *P. truncatus*, to feed within individual cobs with their sheaths intact until most of the grains have been consumed, before dispersing to attack other cobs.

In other West African studies, removal of the husk before storage resulted in an increase in losses of 10-15% over a 4-month storage period, unless the dehusked cobs were protected by insecticide (FAO, 1980). In some regions, infestations of *S. cerealella* appear to be particularly serious if dehusked cobs are stored without insecticide treatment (Schulten, 1976).

Biological constraints on pest population development

COMPETITION

One possible reason for the more serious nature of *Prostephanus truncatus* infestations in Africa, compared to Central America, is that in Africa populations of the larger grain borer appear to be less constrained by competition with other primary pest species such as *Sitophilus zeamais* or *Sitotroga cerealella*. Data on the interactions between these species in their natural storage environment are scarce. Results of a farm storage survey in Honduras indicated that 90% of the samples infested by *P. truncatus* were also infested by *S. zeamais*, although there was no relationship between the numbers of the two species present in individual samples (Hoppe, 1986). Similarly, away from the drier regions of Tanzania, *P. truncatus* and both *S. zeamais* and *Sitophilus oryzae* are commonly found together in stored maize.

In a series of laboratory experiments, Howard (1983) investigated competition between *P. truncatus* and *S. zeamais*, under different environmental conditions. When confined in glass jars, on maize grains stabilized with a layer of glass beads, *S. zeamais* dominated the interaction with *P. truncatus* at temperatures of less than 28°C (r.h. was approximately 70%). Above this temperature, *P. truncatus* predominated. When confined on artificial cobs (maize grains embedded in cellulose filler coated onto wooden blocks) *P. truncatus* dominated at temperatures of above 28°C. At temperatures lower than 28°C, the results suggested that the outcome depended on which species is first to infest the maize and the length of time for which the 'pioneer' population develops unchallenged.

Howard (1983) suggested that, at least initially, the differing oviposition behaviour of the females (*P. truncatus* females lay eggs in tunnels near the base of the grain, whereas most female *S. zeamais* deposit their eggs around the crown) would tend to keep the larvae of the two species spatially segregated. In addition, when at least 50% of the food medium had been turned to flour, generated in large quantities in a *P. truncatus* infestation, *S. zeamais* larvae developed in the flour between grains, rather than in the grains themselves, and thus reduced larval competition with *P. truncatus*.

Haubruge and Verstraeten (1987) examined the interactions between *P. truncatus* and four other species commonly found in maize stores; *S. zeamais*, *Triboliom castaneum*, *Rhyzopertha dominica* and *Oryzaephilus surinamensis*. Different combinations of these species (as adults) were confined on shelled maize at 30 °C and 70% r.h. for 6 weeks. The results indicated that, in general, development of *P. truncatus* populations is partially inhibited by competition from *T. castaneum* and *S. zeamais*, but not by *R. dominica* or *O. surinamensis*. There was also evidence that *T. castaneum* populations developed faster on whole maize grains, in the presence of *P. truncatus*, than would otherwise be the case. This probably reflects the role of the two species as secondary and primary pests of whole maize grains respectively.

Markham (1981) studied the distribution of insects within an experimental maize crib over a 6-month storage period, from August to January (wet season) in south-west Nigeria. The distributions of the two main primary pest species, *S. zeamais* and *S. cerealella* were positively correlated, probably as a result of the independent correlation of both species with environmental parameters, such as temperature or grain moisture content. Of the two, *S. zeamais* was clearly the dominant species. It has been shown that at insect densities similar to those in Markham's study, *S. zeamais* can cause severe mortality to *S. cerealella* larvae (Ayertey, 1979; 1980). Chesnut and Douglas (1971) also consider that *S. zeamais* has a reproductive advantage over *S. cerealella*, because of its longer adult life-span. In field trials in Zambia, Hindmarsh and MacDonald (1980) noted that these two species tend to avoid direct competition with each other by the timing of their attack. *S. cerealella* numbers built up rapidly during the dry season and peaked at the beginning of the rains, when the moisture content of the grain was below 12%. The numbers of *S. zeamais* peaked 3 months later, at a time when the moth population had begun to decline markedly.

PARASITISM AND PREDATION

A number of species of natural enemy are associated with the indigenous pests found in African maize stores. In an experimental maize crib in Nigeria, distributions of the two commonest hymenopteran parasites present, *Chaetospila elegans* and *Cerocephalia dinoderi* (both Pteromalidae) were positively correlated with that of *S. zeamais.* The distributions of two species of anthrocorid predator *Lyctocoris cochici* and *Scolpoides divareti* were not correlated with that of the main primary pests, but were correlated with that of the secondary pests, such as *Carpophilus, Gnatocerus,* and *Cryptolestes* spp. (Markham, 1981). At present, it is unclear whether any of the indigenous species of insect predators or parasites have adopted *P. truncatus* as a host in African maize stores.

In Costa Rica a small number of natural enemies have been found in association with maize heavily infested by *P. truncatus* (Boeye, *et al.*, in press). The two species of parasitic wasp recorded – *Anisopteromalus calandrae* and *Chaetospila elegans* (both Pteromalidae) are cosmopolitan and are known to parasitize several different storage pest species. Large numbers of *A. calandrae* have been seen in Tanzanian stores heavily infested with *P. truncatus* (Hodges, unpublished).

Of the two predator species found in association with *P. truncatus* in Costa Rica – an anthrocorid of the genus *Calloides* and the histerid beetle *Teretriosoma nigrescens* – neither species is known to be present in Africa. The latter species, *T. nigrescens,* has been shown to be an extremely effective predator of *P. truncatus* in laboratory trials (Rees, 1985; 1987). Both the larvae and adults of *T. nigrescens* feed on the larval stage of *P. truncatus.* When confined in glass jars, on loose grains weighted down with glass beads, the introduction of 10 *T. nigrescens* adults prevented populations of 25, 50, 75 and 100 *P. truncatus* from increasing over a 7-week period, during which time single species control populations of *Prostephanus* increased at least 10-fold.

In Costa Rica, large numbers of adult *T. nigrescens* have been caught within maize fields in traps baited with *Prostephanus* pheromone, indicating that this predator is capable of locating *P. truncatus* over much greater distances than those found within the confines of maize stores (Boeye *et al.,* unpublished). In the laboratory, *T. nigrescens* adults appeared to be strongly attracted to small quantities of frass and damaged grain from a *Prostephanus* culture, when this material was placed within a 1 kg bulk of clean shelled maize. The response was apparent even when heat treatment or acetone was used in an attempt to remove any traces of *Prostephanus* pheromone which may have impregnated the frass or damaged maize. This suggests that *T. nigrescens* is capable of responding, at least over a short distances, to more than one stimulus associated with *P. truncatus* infestation of maize (Rees, unpublished). The results of both the field and laboratory studies strongly suggest that *T. nigrescens* is a host-specific predator of *P. truncatus.*

To provide information on the likely effect of introducing *T. nigrescens* into the environment in Tanzania, Rees (1987) conducted a series of laboratory trials in which *T. nigrescens* was confined on cobs (with their sheaths intact) already infested with *P. truncatus*, or with both *P. truncatus* and either *T. castaneum* or *S. zeamais*. When *P. truncatus* was the only potential host available to *T. nigrescens*, the rate at which populations of *Prostephanus* increased was reduced by a factor of between 10 and 4, when the predators were introduced after 3 or 6 weeks, respectively. *T. nigrescens* had little effect on numbers of *S. zeamais* or *T. castaneum* when they were present on the cobs. Nor did *T. castaneum* have any significant effect on the predatory ability of the *T. nigrescens* population. Perhaps most importantly, selective predation of *P. truncatus* by *T. nigrescens* did not encourage significant increases in the populations of *S. zeamais* or *T. castaneum*. Whether this pattern of results would be repeated on shelled maize requires investigation.

ENTOMOPATHOGENS OF *PROSTEPHANUS TRUNCATUS*

Schulz and Laborius (1987) examined the internal and external microflora of adult *P. truncatus* infesting stored maize. From approximately 80 bacterial isolates tested by topical application on the insect mouth parts, only 2 proved pathogenic. Similar experiments were performed with fungal spores isolated from dead *P. truncatus* adults. A number of toxic species were found, but many of these, such as *Aspergillus* spp., are also toxic to mammals and thus seem of limited potential for exploitation against *P. truncatus*. Two species of insect fungi, *Beauveria bassiana* and *Metarhizium anisopliae*, caused heavy mortality of *Prostephanus* when fungal preparations were dusted onto maize cobs infested by the beetle (Boeye *et al.,* in press).

Another potentially promising result from this microbiological research was the discovery of an acutely lethal protozoan of the genus *Mattesia* in *P. truncatus* populations in Togo (Lipa and Wohlgemuth, 1986). This pathogen appears to be widely distributed within *Prostephanus* populations in Togo, although the rate of infection is low; 1-2% of adults in affected populations (Leliveldt *et al.,* 1988). Distribution of the protozoan appears to be less widespread in Central America and Tanzania than in Togo (Boeye *et al.,* in press). The applicability and longevity of infective material, its interaction with chemical control inputs and other factors which will affect the efficacy of *Mattesia* in the natural environment require further study.

HOST PLANT RESISTANCE OF MAIZE VARIETIES TO STORAGE PESTS

It is generally true that the maize varieties traditionally grown by farmers in a particular area will have evolved some degree of resistance to local pest populations. Unfortunately, because none of the major maize breeding centres has incorporated resistance to post-harvest pests into their breeding programmes, many new, high-yielding cultivars are more susceptible to attack by storage pests than the poorer yielding varieties they are intended to replace.

Dobie (1974, 1977) investigated inherent resistance to attack by *S. zeamais* and *S. cerealella* of a large number of genotypes held at Centro International de Mejoramiento de Maiz y Trigo (CIMMYT)'s maize seed bank in Mexico. There was a good linear relationship in the susceptibility of maize varieties to the two species, although *S. cerealella* varied much less in its response to different maize varieties than did *S. zeamais*. For this reason, most of the screening work concentrated on identifying resistance to *S. zeamais*.

One characteristic which confers resistance to the maize weevil is complete husk cover. As this attribute can easily be assessed by visual inspection, screening for its presence or absence does not require detailed methodology.

However, as the husk can be damaged by field pests, or may be removed at harvest, it is important that the maize grains themselves should also exhibit resistance to post-harvest infestation. In preliminary trials, Dobie (1977) screened varieties for 'grain hardness' by measuring the average power used by an electric motor to grind a sample of grain, or the proportion of the grain retained by a fine sieve following grinding in a mill (effectively a measure of the ratio of floury to corneous endosperm). The results of these tests showed a significant positive correlation between 'hardness' and susceptibility to infestation by *S. zeamais*. However, there was no correlation between the hardness of a particular genotype and the number of eggs laid by females. This suggests that although few varieties of maize have a testa which is sufficiently strong to prevent females chewing holes in which to lay their eggs, the ability of larvae to feed on and tunnel into the grains is determined, at least in part, by the hardness of the grain.

Taking these results into consideration, Dobie developed a single, standard screening procedure. Adult *S. zeamais* of known sex and age (0-7 days old) were placed on 'conditioning' replicates of the maize varieties to be tested. This allowed the adults to adapt to the change from the variety on which they were cultured, to the variety being screened. After 7 days the adults were transferred from the conditioning replicates to 'test' replicates of the same variety. Any dead adults were replaced at this stage. After 7 days on the test material, the adults were removed and discarded. The grains were then left undisturbed until the first F1 individuals began to emerge. Thereafter, emerged insects were removed and counted daily until all F1 adults had emerged.

The total number of emergences and the median development period were derived from the data and used in the calculation of an 'index of susceptibility'

$$\text{index of susceptibility} = \ln N / t \times 100$$

where N = total number of F1 adults
t = median development period

Using this method to screen a large number of maize genotypes, Dobie (1974) confirmed that the most important characteristic influencing susceptibility to *S. zeamais*, appears to be grain 'hardness'.

Serratos *et al.* (1987) examined factors contributing to the resistance of maize varieties from Belize to infestation by *S. zeamais*. Their screening procedure differed from Dobie's, but the results of choice tests, in which they examined food consumption and production of F1 progeny separately, again indicated that resistance was strongly correlated with mechanical hardness.

Only a few limited studies of varietal susceptibility of maize to *P. truncatus* have as yet been published. Ramirez and Silver (1983) examined the development of *P. truncatus* on a limited number of varieties using X-ray photography. The use of X-ray photographs to determine the number of eggs, larvae, pupae, and adults within each maize grain resulted in a significant underestimate of oviposition rate. Free-choice and non-choice tests also produced contradictory results for the numbers of eggs laid and numbers of F1 adults produced on different varieties. The authors concluded that those genotypes with soft pericarps and a high lysine and tryptophan content were most vulnerable to attack by the beetle.

Howard (1984) compared the susceptibility of 10 maize varieties to attack by *P. truncatus* and *S. zeamais* using the numbers of F1 adults, percentage of damaged grains and weight loss as indicators. For each variety, adults were presented with loose grains, grains weighted down with glass beads and grains stuck onto wooden blocks to form artificial cobs. For both species, all three parameters indicated that popcorn varieties were least susceptible and flint varieties less susceptible than either floury or dent maize.

These results suggest that the selection of new, high-yielding cultivars with the 'opaque-2' gene in their genome (conferring a high lysine and tryptophan content, as well as a soft pericarp) is likely to increase the susceptibility of stored maize both to *P. truncatus* and to *S. zeamais*. In contrast, the selection of varieties with flinty grain is likely to reduce post-harvest losses, but is equally likely to have an adverse effect on yield potential. Plant-breeders and farmers alike must therefore weigh up the costs and benefits of selecting for resistance to storage pests.

Protection of stored maize (and cassava) with conventional insecticides

The use of conventional insecticides to reduce storage losses to food crops has become increasingly common in recent years. However, while storage structures or containers such as gunny bags can be treated with residual insecticides without serious risk of contaminating the stored food, only chemicals with a relatively low mammalian toxicity can be recommended for direct application to food grains. Suitable 'contact' insecticides can be applied either as a liquid spray or as a dust for admixture with the grain. To obtain even coverage of the commodity, contact insecticides should be applied before or during loading of the store. Treatment of the surface layer of cobs within a crib using an insecticidal spray can also be effective, but re-spraying at monthly intervals may be necessary, as those aspects of crib design which allow the maize to continue to dry after storage also increase the rate at which insecticides break down, particularly on the surface of the crib. Some insecticides, such as pirimiphos-methyl, applied as a spray to the surface layer of cobs, appear to vaporize and thus have an effect somewhat similar to fumigation.

In general, once stores have been filled with maize, the only effective method of treating subsequent infestations is by fumigation. However, the cost of fumigating large numbers of small stores containing a relatively low-value crop such as maize, and the acute toxicity of fumigants, reduce the suitability of fumigation in small-scale, farm-storage situations. A further disadvantage is that fumigants have no residual activity and reinfestation of the stored maize can take place rapidly.

PRE-HARVEST INSECTICIDE TREATMENT

In the southern United States, spray applications of insecticide on growing maize plants, 7 weeks and 3 weeks before harvest, reduced by 90% the number of ears infested with the predominant pest, *Sitophilus oryzae*, in comparison with untreated control plants (Floyd and Powell, 1958). Unfortunately, the authors did not provide any indication of the cost-effectiveness of these sprays in reducing losses during storage. Trials have been conducted to examine the effect of insecticide control of Lepidoptera attacking maize cobs in the field, on the levels of storage insect infestation at harvest (Cornes *et al.*, 1966). The application of carbaryl to the growing crop was shown to be ineffective in reducing the number of cobs damaged by field insect pests or the number of storage pests present at harvest.

TREATMENT OF HARVESTED MAIZE WITH CONTACT INSECTICIDES

The results of some studies carried out to determine the optimum use of insecticides on stored maize, for control of pest complexes dominated by *S. zeamais* or *Sitotroga cerealella* have demonstrated the benefits of shelling maize before storage and treating loose grains with organophosphorus insecticides. In Zambia, Hindmarsh and MacDonald (1980) reported that admixture of malathion 1% dust, tetrachlorvinphos 3% dust, jodfenphos 2% dust (all at

12 p.p.m.)*, pirimiphos-methyl 2% dust (4 p.p.m.) or fenitrothion 1% dust (2 p.p.m.) all restricted the percentage of shelled grains with visible insect damage to less than 5%, over a 7-month storage period.

In many parts of the tropics farmers prefer to store maize on the cob, shelling it immediately before consumption. Treating dehusked cobs appears to be more effective than treating cobs with their husks intact; the husk effectively shields any insects inside from contact with the insecticide. In trials in West Africa carried out to test the use of insecticides with improved crib designs, permethrin dust applied to dehusked cobs proved more effective than lindane, bromophos, malathion or pirimiphos-methyl, but all treatments resulted in more than 5% damaged grains after 5 months in store (FAO, 1980). In trials using dehusked cobs stored in an improved crib in Nigeria, permethrin 1 % dust applied at a rate of 2.5 p.p.m. on dry-season harvested maize effectively suppressed populations of *S. zeamais*, and *Tribolium*, *Cryptolestes* and *Carpophilus* spp. for 6 months (Adesuyi, 1982). On maize harvested during the wet season, 10-15 p.p.m. of permethrin were required to achieve similar levels of control.

Early work on the use of insecticides against *P. truncatus* in Central America largely concentrated on the organophosphorus compounds which were recommended for the control of other common maize pests (Giles and Leon, 1974). Malathion, tetrachlorvinphos, lindane and pirmiphos-methyl were applied as 2% dust formulations at 12.5 p.p.m. (based on equivalent shelled grain weight) on dehusked cobs, and at 27.4 p.p.m. on cobs with husks intact. Measurements of percentage of externally damaged grain showed that the ears without husks suffered much less damage than those with husks intact. For both intact and dehusked cobs, malathion provided the most effective protection, although for all treatments, 50% or more of the grains had been visibly damaged by the end of the 24-week storage period. With shelled grains held in small open tins, pyrethrins or bioresmethrin synergized with piperonyl butoxide (2.5/20 p.p.m.) gave satisfactory control for storage periods of up to 24 weeks, markedly out-performing malathion, lindane and pirimiphos-methyl.

Following the outbreaks of *Prostephanus* in West and East Africa, a more comprehensive investigation of insecticide efficacy against this pest has been undertaken. In topical application tests (5-10 day-old adults received 0.05 μl of insecticide solution, applied by microbore syringe to the lateral surface of the 4th abdominal segment) permethrin, deltamethrin, fenvalerate and phenothrin (all pyrethroids) were more effective than the organophosphorus compounds tested, lindane and carbaryl exhibiting an intermediate effect (Golob *et al.,* 1985). The exposure of adults to insecticide-treated maize grains (a local Tanzanian variety, tumble-mixed with dilute dust for 15 minutes and then placed in beakers with glass beads for stabilization) for 14 days at 1, 4, 12 and 24 weeks after the grain had been treated, showed that permethrin (2.5 and 5 p.p.m.) maintained its activity for longer and gave better control after 12 and 24 weeks than methacrifos, chlorpyrifos-methyl or pirimiphos-methyl. Only permethrin and permethrin mixed with pirimiphos-methyl (4+1 p.p.m.) continued to prevent the development of any F1 progeny more than 24 weeks after treatment.

The greater susceptibility of *P. truncatus* to pyrethroids than to organophosphorus compounds was confirmed in laboratory trials in Kenya. The percentage knock-down and percentage mortality of adults after 24 hours 'and 7 days' exposure respectively to treated grains indicated that permethrin and natural pyrethroids were more effective against *P. truncatus* than a range of organophosphorus insecticides. Only tetrachlorvinphos had a comparable effect to these two pyrethroids. When population development over 4-and 6-month periods on treated grain was assessed, deltamethrin gave as good control as permethrin and pyrethrins. Again, tetrachlorvinphos was the most effective organophosphorus insecticide (Muhihu and Kibata, 1985).

*p.p.m. = parts per million.

Hodges and Meik (1984) also investigated other aspects of insecticide application for the control of *P. truncatus.* Preliminary investigations in the laboratory showed that the adult beetles confined on maize cobs have a strong tendency to bore into the base of the core before attacking the grains, presumably because this is the softest part of the cob. Dipping the cores in 0.1% w/v aqueous dispersion of permethrin (prepared from a 25% emulsifiable concentrate), reduced the degree of infestation by 80% compared to the untreated controls, without producing any detectable permethrin residues on the grain. However, field testing of this method in Tanzania proved inconclusive (Golob, unpublished) and its recommendation as a standard method for widespread use would not be desirable as it would involve dilution of concentrated, toxic chemicals by untrained personnel.

Field testing of insecticides against *P. truncatus* at Tabora, in Tanzania (Golob *et al.,* 1985; Golob, unpublished) indicated that maize cobs were more heavily damaged by *Prostephanus* than shelled grain, and confirmed the laboratory findings that pyrethroids are more effective against *P. truncatus* than organophosphorus insecticides. On the basis of these results, farmers were recommended to protect their maize first by shelling it and then by admixing it with 0.5% permethrin dust applied at 3 p.p.m. of active ingredient (Golob, 1984). In southern Kenya, application of 0.5% permethrin dust at 2.5 p.p.m. to shelled grain in farmers' stores gave satisfactory control *P. truncatus,* restricting losses to approximately 2% over a 9-month period (Muhihu and Kibata, 1985). In these trials, application of 1% pirimiphos-methyl resulted in similar loss levels to those sustained by maize treated with permethrin. However, as other species which infest stored maize, such as *S. oryzae* and *Tribolium castaneum,* are known to be less susceptible to pyrethroids than to organophosphorus insecticides (Golob *et al.,* 1985) the possibility that the widespread use of permethrin may elevate the pest status of other species has been investigated.

In laboratory trials, Hodges and Meik (1986) exposed 4-7 day-old adults of a number of species to maize admixed with permethrin dust, at rates of 1.5, 3.0 and 6.0 p.p.m. After 26 days, adult survival of both *S. zeamais* and *S. oryzae* remained above 50% at the 3.0 p.p.m. treatment level. At 6.0 p.p.m., survival of *S. oryzae* was reduced to almost zero, whereas more than 30% of the *S. zeamais* had survived. There were no obvious sublethal effects on reproduction in either species. *T. castaneum* was more tolerant of the insecticide. Adult survival remained uniformly high at all treatment levels, although the numbers of F1 progeny were reduced, most markedly at the highest dose. In repellency tests female *T. castaneum* laid significantly fewer eggs on treated maize grains. *Gnatocerus maxillosus* was highly susceptible to all doses of permethrin.

In laboratory experiments in Togo, only a combination of organophosphorus and pyrethroid insecticides (1.5% fenitrothion dust plus 3% fenvalerate dust, at 5 and 1 p.p.m., respectively) controlled mixed populations of *P. truncatus* and *S. zeamais* infesting loose grains of a local maize variety (Krall, 1987). In Tanzania, the reported failure of the recommended treatment to control *S. zeamais* populations in humid environments (Mushi, unpublished) appeared to confirm these laboratory results and necessitated a change from the recommended use of permethrin dust on its own, to a 'cocktail' of permethrin and pirimiphos-methyl dust (3.3 and 17.7 p.p.m., respectively). Although deltamethrin is known to be more effective than permethrin against both *P. truncatus* and *S. zeamais* (Evans, 1985), its use is not recommended in Tanzania, as it cannot readily be formulated locally.

Recently, studies have been initiated to determine whether insecticide treatment can provide satisfactory protection of maize cobs against *P. truncatus,* thus allowing farmers to store their maize in the traditional manner. Golob (unpublished) showed that spraying cobs with a liquid formulation of permethrin plus pirimiphos-methyl controlled both *P. truncatus* and *S. zeamais.* To give the desired coverage of the cobs, they were laid on the ground inside a marked metre square, which was then sprayed with the correct volume for

1 m^2 of surface area. Those cobs sprayed with pirimiphos-methyl (1.0 g/m^2) only, suffered the same weight loss as the control cobs (sprayed with water), although the number of *Sitophilus* was reduced. Treatment with permethrin (0.2 g/m^2), or permethrin and pirimiphos-methyl achieved adequate control of both *P. truncatus* and *S. zeamais* for up to 6 months.

The efficacy of cob-spraying treatments was greatly increased by storing the cobs in a mud-lined 'vihenge' (a traditional Tanzanian storage container made from a large woven basket, set on poles and covered with a thatched roof). Whereas maize cobs sprayed with permethrin and stored in an open crib sustained a weight loss of 17.7% over a period of 8 months, those stored in the mud-lined vihenge sustained only 3.1% weight loss during the same period (Golob, unpublished). The successful control of both *P. truncatus* and *S. zeamais* resulted from the action of the mud wall, both in forming a physical barrier to insect infestation and in producing an environment inside the store in which insecticide activity was enhanced and prolonged.

There is now some degree of discord in the literature over whether pyrethroids in general and permethrin in particular can provide adequate protection of maize against both *P. truncatus* and *S. zeamais*. This may reflect, at least in part, the different methodologies used to test insecticide applications. In particular, the timing of a spray or dust treatment with permethrin appears to be critical to its effect on *S. zeamais* populations (Golob, personal communication). Where applications of the recommended insecticide, at the correct dosage, appear to have failed to prevent damage, this may have resulted from the presence of a significant infestation within the maize before treatment.

TREATMENT OF CASSAVA WITH CONTACT INSECTICIDES

Cassava is an important alternative host for the larger grain borer. As such, the treatment of cassava with insecticide to prevent infestation by *P. truncatus* may be important in the control programmes which aim to reduce losses sustained by maize as a result of infestation by the pest. Some work has been done on the use of insecticides to protect cassava against *Prostephanus*. Senkondo (1984) dipped dried cassava roots in insecticidal dispersions to give treatments of deltamethrin (0.5 and 1.0 p.p.m.), permethrin (1.25 and 2.5 p.p.m.) or pirimiphos-methyl (5.0 and 10.0 p.p.m.), or dusted cassava with a dilute dust of permethrin to give a treatment of 2 p.p.m. Adults were then confined on the cassava for 45 days, beginning immediately after, or one month after treatment. Both dipping treatments of deltamethrin, the permethrin dipping treatment at 2.5 p.p.m., and the permethrin dusting proved effective against adults introduced after one month. These treatments remained effective for 6 months.

In field trials in Tanzania, cassava tubers were dipped in 0.005% or 0.01 % solutions of permethrin for 20 seconds, before drying and storage in an experimental crib (Golob, unpublished). Neither treatment significantly reduced the numbers of *P. truncatus* or *S. zeamais* adults present (per kilogram of cassava) after 4, 8, 12 or 19 weeks, in comparison with controls sprayed with water. In Togo, cassava roots have been successfully protected by dipping them in a 1 p.p.m. solution of deltamethrin for 2 minutes immediately after peeling, followed by 2 weeks of sun drying. However, it is not clear whether the insecticide residue levels resulting from this treatment were acceptable.

TREATMENT OF STORAGE STRUCTURES WITH CONTACT INSECTICIDES

Experiments have been carried out to investigate the potential for effective control of *Prostephanus* by treating storage structures or containers used for transport of grain with residual insecticides (White, 1982). Test materials were treated with insecticide and then bioassayed at 4-week intervals up to 16 weeks. The overall conclusions suggest that treating concrete with malathion or pirimiphos-methyl will not provide lasting protection against *P. truncatus*. On plywood, both malathion and pirimiphos-methyl caused 70-95% mortality of adult beetles after 16 weeks.

FUMIGATION OF INFESTED STOCKS IN STORAGE

Fumigation with phosphine seems to be as effective against *P. truncatus* as it is against susceptible strains of other storage insects. Krall (1984) reported successful control of *P. truncatus* in Togo, where whole maize cribs were covered with thin plastic fumigation sheets and fumigated with phosphine applied at 5g /m^3 for an unspecified period. There are no available reports on the susceptibility of *P. truncatus* to methyl bromide. The need for specialized equipment with which to apply methyl bromide makes this compound less suitable than phosphine for the fumigation of farmers' stores.

In view of the number of phosphine fumigations which are being carried out against *P. truncatus*, testing of field populations in Tanzania and Togo for resistance to phosphine may have to be considered in the near future.

Use of plant material and minerals to protect stored maize

Traditionally, a wide range of plant substances, minerals and ashes has been used by farmers to protect stored maize against insect pests (Golob and Webley, 1980). Generally, these materials do not have an acute insecticidal activity, but serve as a physical barrier or repellent, preventing insects from moving through the grain bulk (Golob *et al.,* 1982). To achieve a significant reduction in the levels of infestation, a higher concentration of the protectant is usually required than is necessary when using conventional insecticides.

In field trials at Tabora, a number of materials were tested for efficacy against *Prostephanus truncatus* and *Sitophilus zeamais*, by admixture with shelled maize. Each treatment was then placed in a sack and stored in a compartment of an experimental crib. In the initial trials a number of additives, including rotenone, neem, pyrethrum, paddy-husk ash, wood ash and sand, were shown to give satisfactory control of the natural pest complex for up to 8 weeks (Golob, unpublished). However, after 10 weeks only grain treated with pyrethrum, paddy-husk ash or wood ash had sustained significantly less damage than the untreated control grain. In further trials, paddy-husk ash, wood ash, powdered neem seed and sun hemp seeds were tested. Paddy-husk ash (5% w/w*) was the most successful treatment, the grain suffering only a 3.7% weight loss after 8 months, compared with a 31.8% loss to the untreated control (Golob, unpublished).

*w/w = weight for weight.

Monitoring the spread of the larger grain borer in Africa

Monitoring the spread of *Prostephanus truncatus* populations is essential if the outbreaks in Africa are to be contained. It was quickly realized that to do this adequately by visual inspection of farmers' stores is not feasible. In a series of trapping studies, a 'refuge' trap design already used to monitor other species of stored product beetle was modified to form a cheap and effective trap for adult *P. truncatus* (Hodges *et al.,* 1983b; Hodges *et al.,* 1984). The trap was baited with one component of the aggregation pheromone produced by adult male *Prostephanus*, given the trivial name 'Trunc-call 1' (T1), and sprayed on the inside surfaces with permethrin at 0.1g/m^2. Left for 2 weeks, in farm stores containing 2,000-3,000 cobs, these traps demonstrated the presence of *P. truncatus* as frequently as the inspection of up to 200 cobs, removed at random from each store. Preliminary work with a second pheromone component, 'Trunc-call 2' (T2), has shown that traps baited with a mixture of these compounds will catch more *Prostephanus* in infested stores than traps baited with T1 alone.

The presence of T2 in the pheromone used as a lure has been shown to produce a similar increase in trap catches of *P. truncatus* in maize fields before harvest. In an experiment carried out in the immediate surrounding area of infested maize stores in Tanzania, 'pot' traps (closed plastic pots, 13 cm high, with holes in the lids 4.5 cm in diameter) set on 1 m high posts were arranged in a matrix, and pheromone vials containing T1, or different ratios of T1 to T2, were allocated to the traps in a latin square design. The traps were emptied at 3-day intervals over a 12-day period without changing the pheromone lure. The results of the experiment showed clearly that mixtures of T1 and T2 attract more insects to the traps than T1 alone (Dendy *et al.,* unpublished).

Similar results were obtained from an experiment using small pot traps, hung from the lower leaves of maize plants, within a crop which was approximately 3 months old. At this stage there were already considerable numbers of *P. truncatus* adults flying within the crop, and these were attracted in greater numbers to traps containing mixtures of T1 and T2, rather than to traps baited with T1 only. The greater attraction to pheromone sources comprising mixtures of T1 and T2, has so far only been demonstrated in trials where the density of insects was relatively high. It is, as yet, uncertain whether using mixtures of T1 and T2 would improve the effectiveness of monitoring operations by detecting the presence of the beetle in stores or fields, when the use of T1 alone would fail to do so.

It may be possible to improve the design of the pheromone traps used to catch flying *Prostephanus*. In initial tests of different trap types, carried out in Tanzanian maize fields 3-4 months after planting, delta and funnel traps caught significantly higher numbers of *P. truncatus* than the pot traps described above (Dendy and Sherman, personal communication). The pot trap may be less efficient than the other two designs because the pheromone vial, positioned on the inside base of the pot, is less exposed to moving air than in the delta or funnel traps.

Behavioural studies in the field revealed that *P. truncatus* attempt to land close to the pheromone source and then walk toward the lure. In the funnel trap the pheromone vial was situated on an almost vertical surface. Insects attempting to land close to the lure fell into the collecting tube below. The vial in the delta trap was located in the centre of the sticky base and insects landing near the lure were immediately caught. However, the pot trap has a horizontal rim round the entrance to the pot and beetles landing on this rim may have flown off, and thus avoided falling through the hole onto the sticky base.

In tests of trap design to maximize the catch of another bostrichid, *Rhyzopertha dominica,* flying within warehouse stores in the southern United States, the Lindgren funnel trap (a number of funnels suspended vertically one above the other with a collecting jar attached below the bottom funnel) had a significantly larger mean capture rate than any of the other designs tested (Leos-Martinez *et al.,* 1987). In further warehouse trials, the performance of the Lindgren funnel trap was compared with that of a Johnston-Taylor suction trap, which in theory assesses actual insect density in a fixed volume of air (Leos-Martinez *et al.,* 1986). Average hourly captures of *R. dominica* in the two trap types did not differ significantly. As there was no indication that the pheromone source appreciably elicited flight activity, the funnel trap appears to provide as accurate a measure of aerial insect density as the suction trap.

Integrated pest management in traditional maize stores

Although the concept of an economic threshold for pest control operations is less applicable to post-harvest systems than to pre-harvest ones (Hebblethwaite, 1985), it is apparent that the level of loss which justifies intensified insect control on farm-stored maize has commonly been reached or exceeded where *Prostephanus truncatus* has become established in Africa. While the emergency control programmes set up to combat this pest have been successful in reducing losses locally, they have failed to stop the spread of the insect. The continued extensive and intensive use of imported insecticides to control the beetle in the maize-producing regions of sub-Saharan Africa is neither practicable nor desirable. Sustainable, flexible and integrated pest management strategies, aimed at the whole spectrum of insect pests attacking maize in on-farm storage, are needed to reduce losses to levels which farmers have traditionally considered acceptable.

The prospects for the development of such strategies have been reviewed by McFarlane (1988). He regards the judicious use of contact insecticides, the use of pheromone-baited traps for monitoring and possibly for control, thermal disinfestation by solar drying, and the use of biological control agents, as the control techniques having the greatest potential value in this situation. However, before these components can be combined into successful pest management strategies, a number of important questions, concerning the basic bionomics of the main pests and their associated species, remain to be answered. Many of these questions relate to the interaction of *P. truncatus* with other components of the maize storage eco-system. Aspects of the ecology of *P. truncatus* which are at present little understood include the origins of field infestation of maize, and the significance of pre-harvest infestation to the overall levels of infestation which build up during storage. Understanding of these matters would be helped by an improved knowledge of the flight activity and dispersal behaviour of *P. truncatus*, and the significance of populations of *P. truncatus* in crop residues within stores to the infestation of subsequent crops while still in the field.

While there has been some work in the laboratory on the relationship between the larger grain borer, other pests and at least one natural enemy, the interactions between these species in the storage environment are, as yet, undefined. Although *Teretriosoma nigrescens* appears to be a specific predator of *P. truncatus*, surveys of maize stores in Central Honduras (Hoppe, 1986) revealed that the predator was present in only 25% of the stores infested with *P. truncatus*. In addition, there was no evidence that the presence of *T. nigrescens* had any limiting effect on *P. truncatus* populations. Studies aimed at determining the effect of chemical control measures against the pest complex on predators and parasites would provide valuable information on the likely stability of pest management strategies which contain a biological control component.

After years of quiescence, international maize-breeding centres are now expressing interest in improving the storing qualities of new, high-yielding maize cultivars. Sources of resistance to *S. zeamais* have already been identified (Dobie, 1974 and 1977). The possibility that some of these genotypes may also be resistant to *P. truncatus* warrants investigation. However, this will require the development of specific techniques appropriate for the identification of maize varieties which are resistant to attack by *P. truncatus*. The incorporation of resistant varieties into integrated pest management strategies for the protection of stored maize should be a long-term goal, whether or not *P. truncatus* continues as the most serious threat to African maize producers.

The development and implementation of integrated pest management strategies for insect pests of maize in traditional small-farm storage in Africa will undoubtedly require a major research and extension effort by national and international agencies. Alternatives to such an approach, for example the continued widespread intensive use of insecticides by farmers, or the regional centralization of storage sites, with the concomitant need for improved transport, packaging and timing of grain movements, would however require a much greater commitment of financial resources by national governments and would almost certainly create new pest problems.

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Appendices

APPENDIX 1: LIFE HISTORY DATA FOR *PROSTEPHANUS TRUNCATUS*

Food medium	Temperature °C	r.h.(%)	Development period (days)	Mortality (%)	Reference
Ground maize:					Bell and Watters, 1982
low density	30	70	33		
high density	30	70	27		
Ground maize	18	70	167	68	
	20	70	84	20	
	20	90	104	56	
	22	70	53	8	
	22	90	79	60	
	25	40	51	16	
	25	70	39	4	
	25	90	44	32	
	27	40	52	40	
	27	70	36	4	
	27	90	40	52	
	30	40	35	20	
	30	70	28	8	
	30	90	44	20	
	32	40	38	36	
	32	70	27	12	
	32	90	32	20	
	35	70	31	36	
	37	70	30	88	
Maize kernels	22	70	56	12	Bell and Watters, 1982
	25	70	41	16	
	27	70	43	16	
	30	70	27	20	
	32	70	27	22	
	35	70	29	42	
Finely ground maize	22	50	L-A 78	53	Shires, 1979
	22	70	L-A 61	30	
	25	50	L-A 50	32	
	25	70	L-A 43	35	
	27	50	L-A 40	33	
	27	70	L-A 37	23	
	30	50	L-A 34	32	
	30	70	L-A 30	13	
	32	50	L-A 33	28	
	32	70	L-A 30	17	
	35	50	L-A 43	67	
	35	70	L-A 40	63	
Finely ground maize	32	80	E 5		Shires, 1980
	32	80	L 25		
	32	80	P 5		

Notes: E egg
L larva
P pupa
A adult

APPENDIX 2: MOISTURE CONTENT OF MAIZE GRAINS BEFORE HARVEST

Geographical location	Days before harvest	M.C. of grain (%)	Mean environment T °C	Mean environment % r.h.	Reference
Kenya (Kitale)	131-126	90			Giles and Ashman, 1971
	117-112	76			
(Crop harvested 145 days after pollination)	103-98	60			
	89-84	52			
	75-70	38			
	61-56	35			
	47-42	32			
	33-28	26			
	19-14	22			
Nigeria	21	57	25	70	Markham, 1981
(Ibadan)	7	30	25	70	
First harvest when crop had reached physiological maturity	1st harvest	30	27	70	
	2nd harvest (+3 weeks)	17	27	70	

APPENDIX 3: DETERMINATION OF MOISTURE CONTENT OF MAIZE

The standard method of determining the moisture content (m.c.) of stored products requires the use of a fan-ventilated oven, aluminium dishes with tight-fitting lids, a desiccator containing a suitable desiccant, such as silica gel, and a fine balance accurate to 0.1 mg.

If the m.c. of the produce is likely to be greater than 18% then a preliminary stage is required to dry the maize down to approximately this level.

Preliminary drying
- weigh the aluminium dish and lid empty
- fill the dish with maize
- reweigh
- leave the maize in the dish in dry, warm conditions, such as a controlled temperature room for an appropriate period
- reweigh

Oven determination
- grind the maize in a laboratory mill
- put the flour into the dish
- reweigh
- preheat the oven to 130°C
- put the open dish and the lid into the fan-ventilated oven and time the exposure period from 10-15 minutes after the door is closed, in order to let the oven return to the desired temperature
- after the maize sample has been exposed to the required temperature for 2 hours, remove the tin from the oven, immediately cover it with the lid and place it in a desiccator
- leave in the desiccator for approximately 1 hour, to allow the sample to cool
- reweigh

Where a preliminary stage is necessary, the % m.c. of the original sample is calculated using the formula:

$\% \text{ m.c.} = [((a \times b/c) + d)/e] \times 100$

where a = moisture loss due to oven drying
b = weight of sample
c = weight of sample used in oven drying
d = moisture loss due to air drying
e = original wet weight of sample

Where only oven determination is necessary, the % m.c. of the sample is calculated using the formula:
$\% \text{ m.c.} = (a\text{-}b/a) \times 100$
where a = original wet weight of sample
b = weight of sample after drying

For each quantity of maize which can be assumed to have a unique m.c., at least three samples in aluminium tins should be used to determine the m.c. As a general rule, the range of values from the separate sample dishes should not exceed 0.2% of the total m.c.

APPENDIX 4: LOSS ASSESSMENT SURVEY RESULTS

Location	Date	Storage period (months)	Weight loss (%)	Assessment method	Reference
Kenya:	1973-74	9	12.7	c. % d.	de Lima, 1979
Malawi:	1978-79	6	3.3	s. v/w	Golob, 1980
Honduras:	1981	6.3	13.9	c. & w.	Hoppe, 1986
	1982	6.3	11.0	c. & w.	
	1983	7.4	10.0	c. & w.	
Tanzania:	1981	3-6	8.7	c. & w.	Golob and Hodges, 1983
Togo:	1983-84	4	7.7	c. & w.	Pantenius, 1988
	1985	6	6.4	c. & w.	
		8	44.8	Sample	

Notes: c. % d. = converted percentage damage
c. & w. = count and weigh
s. v/w = standard volume/weight
Sample = sample weight method described in text

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