ASSESSMENT OF MAIZE (*Zea mays* L.) DAMAGE AND YIELD LOSS DUE TO RODENTS IN THE FIELD

BY

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ABSTRACT

Assessment of damage and yield loss due to rodents was carried out in maize fields in Morogoro, Tanzania. The most abundant rodents in these fields were the multimammate rats, *Mastomys natalensis*. Spatial distribution of damage in maize fields was random for experimental fields planted with maize, located between other maize fields owned by farmers. Four sampling techniques viz: non stratified systematic row sampling, non stratified systematic z-sampling, stratified random square sampling, and non stratified simple random sampling for estimation of maize damage and yield losses due to rodents were compared in terms of precision and accuracy, and time spent for damage and yield loss estimations. The actual rodent damage in 15 maize fields was determined by counting damaged and undamaged maize plants at seedling stage and the actual yield loss was calculated. The actual damage varied from 17.3% to 82% during the period of study. The results showed clearly that non-stratified systematic row sampling is the most robust technique for assessing maize damage and yield loss due to rodents. A standard curve for sampling using this technique is provided. The relationship between rodent density and maize damage at seedling was determined. The best model for the data was determined using Akaike Information Criterium. The best model for the relationship is Sigmoid ($r = 0.74$; $n = 44$; $p = 0.001$). Variations occurred between the observed and predicted line. Damage was low or high depending on the amount of rainfall after planting. Maize seed planting followed by heavy rainfall suffered lower damage than when rainfall was poor, due to inability by rodents to locate the planted seeds. Rodent damage and the resultant yield loss are positively correlated, but only in years with well distributed rainfall. Results from model simulations showed that it is more profitable to control rodents in the fields in February and November or February and October than any other month combinations. This calendar approach for rodent control seems to be most appropriate for the Tanzanian maize growers.

DECLARATION

I, LOTH SIKWESE MULUNGU, do hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my own original work and has neither been submitted nor is it being concurrently submitted for a degree award in any other University.

Signature..

Date............ 10/11/2003 ....

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To all the Mulungu family.

To all people who seek education.

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LIST OF ABBREVIATIONS AND SYMBOLS

π	=	pai
μ	=	Population mean
$\rho(\chi)$	=	Population distribution
σ^2	=	Variance
^0c	=	Degree celcius
a.s.l.	=	above sea level
ACT	=	Actual yield per a given area
cm	=	centimetre
CMR	=	Capture Mark Recapture
E	=	East
FAO	=	Food and Agricultural Organization of the United Nations
g	=	gram
h	=	hour
ha	=	hectare
J	=	joule
kg	=	kilogram
m	=	metre
Max.	=	maximum
MCF	=	Main Campus Farm
Min.	=	minimum
N	=	Sampling unit

pH	=	hydrogen ion concentration
PV	=	present value
s	=	second (time)
S	=	South
SMCF	=	Solomon Mahlagu Campus Farm
sp.	=	species (singular)
spp	=	species (plural)
SUA	=	Sokoine University of Agriculture
TSHS	=	Tanzanian Shillings
TSP	=	Triple Super Phosphate
US$	=	United State dollars
USAID	=	United States of America Agency for International Development
VLIR	=	Flemish Inter University Council
W_o	=	Potential yield in absence of rodent damage
W_p	=	Potential yield at planting

CHAPTER ONE

1.0 INTRODUCTION

In countries where economies depend on agriculture (e.g. Tanzania), rodent infestation can pose a serious threat not only to individual producers but also the welfare of the entire nation in terms of reduced income and widespread food shortage (Bottrell, 1990; Millan, 1990; Jahn *et al.*, 1999). It is estimated that rodents eat or contaminate enough food every year to feed 200 million people worldwide (Gregory, 2002), equivalent to about six times the population of Tanzania. In Tanzania, a large proportion of potential crop yield is lost because of rodent infestation (Mwanjabe *et al.*, 2002). The problem of rodent damage in agriculture is complex, because almost any crop can be attacked by rodents (Taylor, 1972; Fiedler, 1988, Hunter, 2002). Dramatic rodent outbreaks have been reported in many countries where intensive and extensive cultivation of crops is undertaken (Singleton and Dowsley, 1993). These outbreaks, particularly in cereals such as rice, maize, wheat and barley, have caused serious losses and widespread food shortage (Walker, 1990).

Maize (*Zea mays* L.) sustains livelihood for more than 500 million people in Africa, Asia and Latin America (Kajuna, 1995). It ranks the third most important cereal crop after rice and wheat (Singh, 1987). In Africa, maize is grown in all Sub-Saharan countries (Kajuna, 1995). In Tanzania, it is one of the major food crops and grows under a wide range of conditions (Acland, 1971; Rwamugira, 1996).

In Tanzania, several factors including pests and diseases, contribute to the low yield in maize production. Rodent pests are considered a major impediment to maize production (Mwanjabe, 1993). According to Taylor and Green (1976) and FAO (1980), the multimammate mouse (*Mastomys natalensis*) in particular, constitutes the greatest threat to the crop. This species is economically the most important rodent pest in Sub-Saharan Africa and is a true indigenous commensal (Fiedler, 1988). They occur in natural grasslands and thicket, cultivated areas and human habitats (Leirs, 1994). *Mastomys natalensis* cause damage and subsequent losses in maize during the very sensitive young seedling stage and just before harvest (Lawani, 1982; Fiedler and Fall, 1994). At planting, even moderate rodent damage may necessitate late replanting resulting in lower yields (Taylor, 1968; Myllymäki, 1987; Mwanjabe, 1993). Rodent outbreaks in Kenya in 2001 destroyed 30,000 acres of maize (Appendix 1). Rodent outbreaks in the Coast Region of Tanzania caused extensive damage to maize in 1998 (Appendix 2).

Hall (1970) identified various categories of maize loss resulting from rodent damage in fields. They include seed removal and consumption, seedling cutting, weight loss arising from total grain predation at cob ripening and maturity, and loss of viability of maize seeds due to removal of the embryo from the seed. Also the grade of maize seeds affected on the cobs may be lowered due to increased cracked maize and foreign material and objectionable odours (Mkondya, 1977).

Some estimates of yield losses of cereal crops due to rodent damage in farmers' fields have been made in various studies. In Indonesia, for example, rodents cause annual pre-harvest losses of approximately 17%, enough to feed more than 25 million Indonesians for a year (New Agriculturist, 2002). Catling and Yasin (1981) reported that yield losses due to rodent damage in rice fields varied from 5 to 10% in Bangladesh. In Ethiopia, Goodyear (1976) reported that rodents consumed or destroyed up to 20% of the cereal crops in some years.

In Tanzania, rodents are estimated to cause on average 15% yield loss (Makundi *et al.*, 1991) which would mean loss of around 382,673 tonnes per year of the actual yield (FAO statistics, 2000). This amount of maize would be enough to feed 2.1 million people for a whole year (at about 0.5 kg/day/person) or an estimated value of 42.5 million US$ (at 11.1 US$ per 100 kg bag of maize). However, in many locations in Tanzania, this figure has risen dramatically over the last few years, most noticeably in places where rodent outbreaks occur (Mwanjabe *et al.*2002). To day, it is not usuall for small holder maize farmers to report chronic rodent damage of 5 - 15% per annum, rising to more than 80% in certain cropping seasons and locations (Taylor, 1976 & 1968; Mwanjabe, 1997; Mulungu *et al.*, 2003).

For years, researchers have searched for the less costly (in terms of time spent) and reliable (in terms of accuracy) sampling techniques to estimate damage and yield losses due to rodents. In statistical terms, an acceptable method maximises precision while minimising costs (Cochran, 1977). Several sampling techniques of estimating maize damage and yield loss caused by rodents have been evaluated in Southern Asia (Hoque *et al.*, 1986). They include stratified, strip systematic, and simple random sampling. Systematic sampling technique has been used to evaluate maize crop damage in Tanzania. Mwanjabe and Leirs (1997) estimated maize damage caused by rodents in Morogoro and Chunya districts using systematic sampling technique. They reported that damage of maize seedlings in the two districts was 40 to 80%, 1 - 2 weeks after planting. The authors concluded that such damage could cause serious crop loss at harvest. However, information on the relative efficiency of either stratified or non-stratified sampling techniques for crop damage and yield loss estimates in maize fields is not available.

Rodent control techniques such as biological control, cultural techniques and killing by rodenticides only cannot keep rodent outbreaks below damaging levels (Myllymäki, 1987). This is because a prominent resilience capacity can be expected from the high local reproductive rate and the dispersal ability, immigration and survival (Leirs, 1994). Farmers in Tanzania normally take action if pests are present in the fields in large numbers or severe damage is seen which could reduce their revenue (Makundi *et al.*, 1999). Some farmers may respond to the risk of uncertain pest attack by a schedule of prophylactic treatments in which the timing and amount of chemicals are quite independent of actual pest numbers (Myllymäki, 1987; Brown, 1994). The decision is therefore normally taken irrespective of whether the pest will attack the crop or not (Myllymäki, 1987).

Sometimes, a rodenticide is applied not because it is obviously necessary, but because the farmer takes the prevention measures at low cost and effort (Myllymäki, 1987). The increased use of rodenticides, therefore, as a result of prophylactic and opportunistic treatment may not always be economically optimal or ecologically acceptable (Makundi *et al.*, 1999).

Ideally, treatments should be based on the expected losses in revenue due to damage by rodents at certain population density threshold. Treatment should also take into account the net gains of control, that means, the cost of control operation must be known and whether the reduction in damage is high enough to compensate for that cost. To establish this, we need information on the relationship between rodent densities, damage and yield loss. Some studies (Walker, 1987; 1990) have reported a positive linear relationship between insects, damage and yield loss in a rice crop in South East Asia. Arneson (2001) reported that crop damage and yield losses are generally directly proportional to pest population density at low densities, but approaches an upper limit (often 100%) as the pest population increases. However, the relationship between rodent density and maize crop damage/loss is not yet documented.

Therefore, the current study was carried out to establish the relationship between rodent density, maize damage and yield loss. The study also aimed at incorporating this relationship into bioeconomics models that will be used to assess and predict rodent damage and yield losses with or without control measures and to establish the cost of rodent control strategies.

The specific objectives were:

1: to describe spatial pattern and distribution of damage in maize fields.

2: to evaluate crop damage estimation techniques for maize at two different crop growth stages (i.e. seedling, and maturity), in terms of reliability, accuracy and time,

3: to assess maize damage and yield loss at two different crop growth stages and the relationship to rodent density,

4: to use the established relationship and rodent population models to predict maize damage and yield loss.

5: to establish the costs of rodent control strategies in view of predicted damage and yield loss

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Background Information

In Tanzania, during the past few years, there has been a marked increase in acreage planted with maize, although this increase has not always been accompanied by increased yields of the crop (Bitegeko, 1998). Factors leading to limited yield increase are complex (DeRose *et al*., 2001). Ullstrup (1976) argues that there are many problems to overcome before maximum yields can be attained. These problems include yield determining factors; such as genetic make up of the variety, temperature, radiation, nutrient status, soil moisture, soil type, pH, and the growing environment. Socio-economic factors, pests and diseases further keep yields far from maximum. Of the known pests of maize, rodents contribute to the worsening maize production situation in Tanzania (FAO, 1980; Mangalu, 2001).

2.2 Importance of Rodents in Tanzania

The major vertebrate pests in Tanzania are rodents, although birds and other mammals may sometimes affect the crop (Hoppe, 1980). Although rodents are often used as a protein supplement in some regions in Tanzania, they are, however, serious agricultural, storage and household pests throughout the country (Makundi *et al*., 1991). In fact, they do more damage than plant diseases and all other animal pests put together (Hoppe, 1980). Rodents cause direct damage to various commodities by gnawing and feeding and indirect damage by spoilage. They contaminate (with their droppings, urine, hair, and other body parts), deteriorate, and enhance susceptibility to fungal and bacterial infestations during pre- and post-harvest stages (Gregory, 2002). It has been reported that within six months, one pair of mice can eat more than two kilograms of food and deposit about 18,000 droppings (Alberta Agriculture Food and Rural Development, 1996). Food contaminated by mice is about ten times more than what is eaten.

Rodents are reservoirs of many diseases including bubonic plague, typhus, dysentery, rabies, and salmonellosis (Fiedler, 1988; Gratz, 1990, Gregory, 2002). Annual crops such as maize are affected adversely by rodents. Damage ranges from negligible destruction to total crop loss (Mwanjabe, 1993). For example, regional reports from Lindi in Tanzania showed that crop yield loss due to rodents was 85,108 tons (i.e. 71,236 tons for cereal and 13,872 tons for pulse crops) in 1989/1990 (Mwanjabe *et al.*, 2002). These losses could feed 290,669 people in Lindi (i.e. 700g/man/day for cereals and 100g/man/day for pulses). Several reports have been published indicating the extent of damage caused by rodents to maize (Myllymäki, 1987; Leirs, 1989; Key, 1990; Makundi *et al.*, 1991; Mwanjabe and Sirima, 1993; Fiedler, 1994; Mwanjabe *et al.*, 2002). They all suggest that rodents are a serious pest problem in maize fields.

2.2.1 Rodent species involved in maize damage and yield loss

In Tanzania, damage to maize is largely attributed to *M. natalensis* and the Nile rat *Arvicanthis sp* (Taylor and Green, 1976; Makundi *et al.*, 1991). Either one or both species of rodents are found throughout cereal growing areas. Both species have similar ecological requirements, being essentially animals of grasslands, and under natural conditions, feed on grass or grass seeds, supplemented by insects. All have short life spans of one to two years and high reproductive potentials (Taylor and Green, 1976).

In different localities, the African giant rat (*Cricetomys gambianus*), cane rat (*Thryonomys* spp), gerbils (*Tatera* spp), spiny mice (*Acomys spp*), striped grass mouse (*Lemniscomys spp*), crested porcupine (*Hystrix cristata*), ground squirrels (*Xerus spp*) and mole rats, *Tachyoryctes* spp. and *Cryptomys* spp., are found (Makundi *et al.*, 1991; Fiedler, 1994). These species are also pests in maize fields and they cause serious damage to crops before and after harvest (Fiedler, 1988). It is known that some of these rodent species, for example *Thryonomys swinderianus* and *T. gregorianus*, damage maize crops at all growth stages (Fiedler, 1994). However, *M. natalensis* is by far the most important pest species in Tanzania. In one study, more than 98% of the rodents found in maize fields were *M. natalensis* (Massawe, 2003).

2.2.2 Crop damage in relation to crop phenological stages

Many crops are especially vulnerable at a particular phenological stage. Maize is at high risk at the time of sowing, soon after germination (seedling stage) and again from the cob ripening stage onwards (Makundi *et al.*, 1999, Mulungu *et al.*, 2003), but the crop is notr seriously attacked by *M. natalensis* during the main vegetative developmental stage

(Greaves, 1982; Makundi *et al.*, 1999). Maize damage and yield loss functions can change with crop development. These relationships can be determined empirically at different stages of crop development and the yield at harvest can be affected both by brief episodes of pest damage and by the cumulative effects over the season (Coakley, 1990). It is also affected by factors in the physical environment i.e. temperature, rainfall, cultural practices, etc (Walker, 1990, Coakley, 1990). The growth stages of maize were described by Hanway (1963) as shown in Fig. 1. Only two maize growth stages (viz. seed, seedling and maturity) are critically affected by rodents in Tanzania (Mwanjabe, 1993; Makundi *et al.*, 1999).

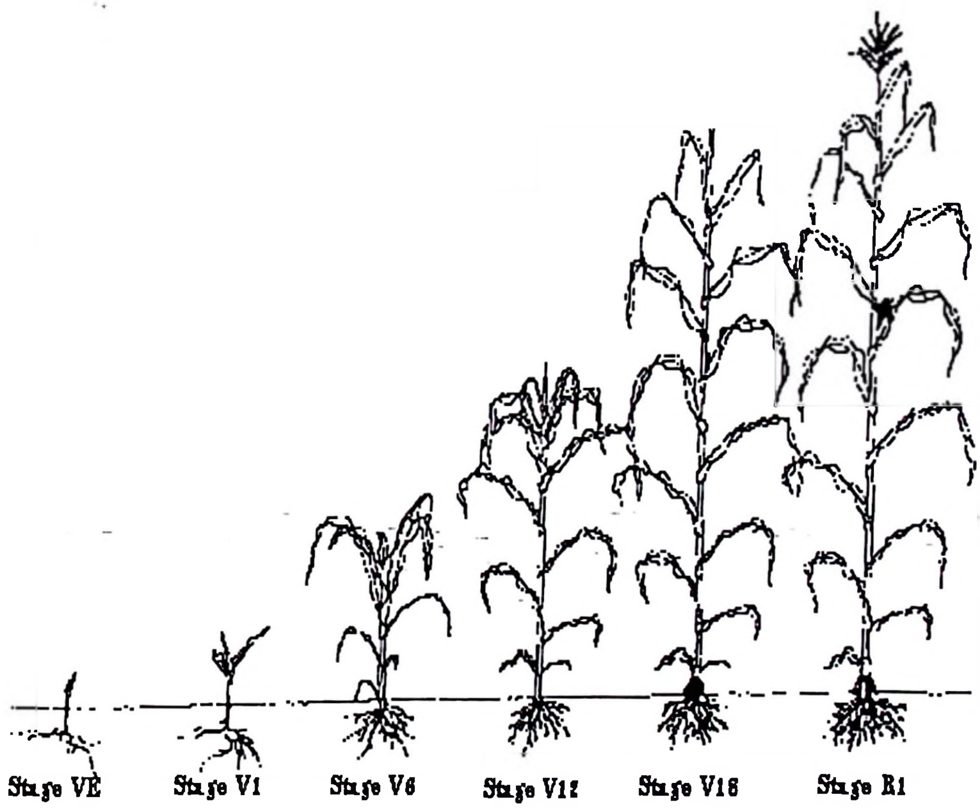


Figure 1: The vegetative growth stages of maize crop.

VE = Seed emergence, V1 = First-leaf stage, V6 = Sixth-leaf stage, V12 = Twelfth-leaf stage, V18 = Eighteenth-leaf stage, R1 = Silking stage.

Maize damage by rodents includes digging up planted seed and damage to mature cobs. Rodents could disrupt a planting programme necessitating repeated replanting (Mwanjabe, 1993; Makundi *et al.*, 1999). Rodent pests dig out seeds extensively immediately after sowing (Reissig *et al.*, 1985). *Arvicanthis spp*, *M. natalensis*, and *Tatera* spp are the major pest species which cause severe damage to maize during the sowing period (Fiedler, 1988; 1994). Greaves (1989) noted that this type of damage at sowing time results in barren patches in the field especially in crops sown in rows. In times of rodent outbreaks, seed retrieval may be so severe that some farmers are forced to replant their fields several times or abandon planting altogether due to shortage of seed (Mwanjabe and Sirima, 1993; Makundi *et al.*, 1999). In other cases the damage does not occur until seedling stage or first leaves have emerged to serve as a marker that enables rodents to locate and dig or pull out the seedlings (Reissig *et al.*, 1985). At the seedling stage, rodents attack the seeds, discarding the stem (Key, 1990) (Plate 1).

Plate 1: Attack of maize at seedling stage by *Mastomys natalensis*.

Greaves (1989) noted that some species, for example *Microtus* spp and gerbils, feed upon the stem and leafy portion of cereal plants early in the season by cutting them off obliquely, 3 - 10 cm above the ground. During the vegetative stage of maize, some species of rodents, (e.g. *Hystrix cristata* and *Xerus* spp) cause crop damage by cutting the stems (Fiedler, 1994). However, damage to crops during the vegetative stage is usually less common and less harmful than at other stages (Makundi *et al*., 1999).

Reissig *et al*. (1985) and Buckle *et al*. (1985) noted that rice tillers were obliquely cut near the base and that the rate or number of tillers cut per rodent per night was dependent on the season and crop phenological stage. The authors found that, damage was severe during the wet season particularly during the vegetative stage of the crop. In contrast, Key (1990) reported that maize damage by striped ground squirrels (*Xerus* spp) in southern Kenya was less in wet planted maize seeds than in dry-planted maize seeds. The author concluded that dry planted seeds exposed to scattered or intermittent rains germinated more sporadically prolonging the susceptible period from about two to several weeks. Also, Pelz (1987) reported that there is an indirect correlation between the extent of damage to sugar beet seeds caused by wood mice (*Apodemus sylvaticus*) and rainfall. The author concluded that, severe damage occurs when sowing is followed by a period of dry weather.

Rodents may climb maize plants and attack the cobs during the reproductive stage (Harris, 1937; Fiedler, 1988). Key (1990) reported a 5.4% cob damage in Kenya, while in Tanzania during an outbreak, rodents could destroy up to 75% of maize cobs (Mwanjabe, 1998). Damage to maize cobs was noted in maize fields in Kilosa District, Tanzania (Plate 2)

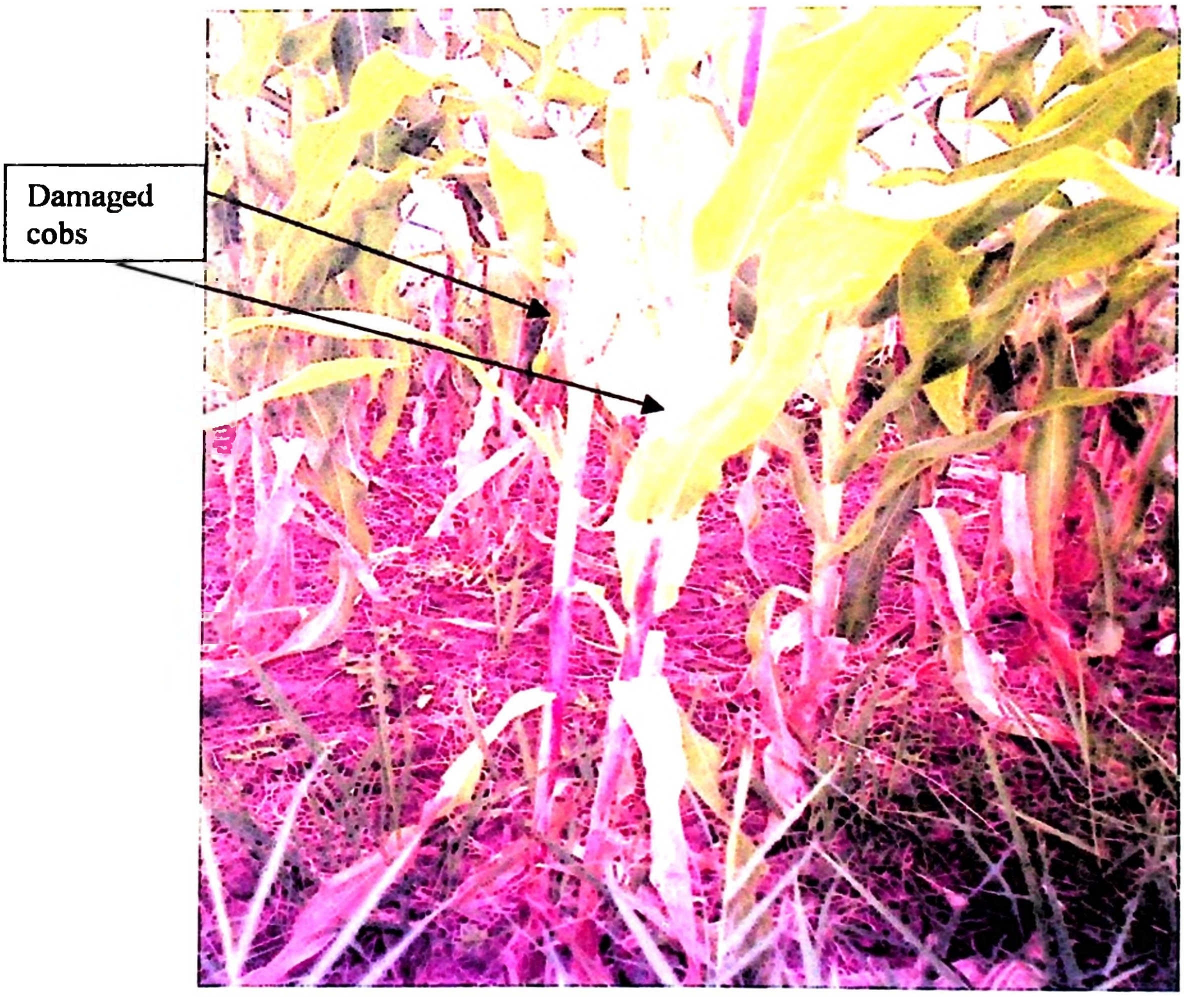


Plate 2: Maize cobs damaged by *Mastomys natalensis* in maize fields at Ilonga, Kilosa District, Tanzania.

The maize ear is the part of the plant destined for human consumption, and is subject to attack by *M. natalensis* (FAO, 1980). The husks covering the ears are pulled open or the whole ear is stripped of the grains. Usually the ears are eaten lengthwise in a longitudinal row (Plate 3) or in a circle around the ear from the tip (Plate 4). Rodents seem to prefer maize in the dough stage of the kernels. Damage to mature maize decreases with increasing hardness of the grain (Hamelink, 1981).

In terms of rodent management, some farmers in many areas in Tanzania reduce rodent damage by wrapping the damaged cob area with plant leaves (Plate 5). This type of damage reduction was also reported by Hunter (2002) as an indigenous method for damage reduction in the Maldives.

Plate 3: Strip damage by *Mastomys natalensis* in maize cobs (by courtesy of the late P.S. Mwanjabe)

Plate 4: Circular damage *Mastomys natalensis* in maize cobs (by courtesy of the late P.S.Mwanjabe)

Plate 5: Cobs wrapped in maize leaves to reduce attack by *Mastomys natalensis* in maize fields at Ilonga, Kilosa District, Tanzania.

2.2.3 Crop damage in relation to different cropping patterns and soil tillage practices

There are two different cropping patterns for maize production in Tanzania; either monocultures or inter-cropping in row or random planting (Temu *et al*., 1995). Among farmers practising conservation tillage, there is considerable concern that rodents can become a serious problem due to the increased vegetation, or "rodent cover", left on the soil surface (Singleton and Redhead, 1990). However, whether or not rodent populations increase and cause economic damage in a particular field with a particular cultivation or planting, depends on many factors. These include the species of rodents, the phase of its population dynamics, reproductive conditions, the history of the field, the type of edge surrounding the field, weather conditions (Mwanjabe, P.S. personal Communication, 2001). The crop type and crop growth stages affect the potential for rodent damage (Walker, 1990).

Rodents are able to exploit the planting practices of farmers and forage more often in the line of planting (Key, 1990). Greaves (1989) and Mwanjabe (1993) reported the influence of different cropping patterns and soil tillage practices on rodent damage in maize fields. They observed that maize seeds sown in rows were more severely damaged by rodents at planting time than those planted randomly. Probably this is because of the variations of distances between the holes in random planted fields are large in which discourage the rodents to search for the seeds.

The fact that farmers cultivate maize in small plots surrounded by fallow fields and bushes (i.e. mosaic fields) creates a favourable environment for rodents to multiply due to ample food and shelter (Taylor, 1972). Many wild rodent species require vegetation cover for protection from predators and for nesting sites (Fiedler, 1994). Greaves (1982) reported that *M. natalensis* could infest patches of bush neighbouring maize fields from which they can re-infest crop fields. Therefore, one would expect that a maize crop planted in fields surrounded by bushes would be more prone to rodent attack than large fields with clean surroundings. In contrast, Kaukeinen (1984) reported that, sometimes, fields surrounded by bushes may not be affected by rodents because bushes may be for nesting only, and not necessarily for feeding in the neighbour maize fields. According to Taylor (1972), there is an inverse relationship between rodent damage and maize field size. Damage on edges tends to be higher than inside the fields. For this reason, small fields are more seriously damaged since they have relatively much more edge than large fields. Everard (1966) reported that small plots surrounded by tall grass, which is the natural habitat of savannah species such as *Arvicanthis* spp. and which, in many cases, harbours several other rodent species as well, showed the typical more clumped damage in peripheral than that recorded in the centre as compared with the larger fields which showed a regular damage distribution.

Both monoculture and intercropping of maize may have an influence on population density build-up. Taylor (1972) reported that large areas of monoculture are less favourable to *M. natalensis* than an inter-cropping pattern. In Australia, mouse outbreaks are said to be due to changes in traditional cropping patterns and land management practices which include increased frequency of cropping, a more diverse range of crops, stubble retention, minimum tillage and direct drilling (Singleton and Dowsley, 1993). According to the authors, the factors give favourable conditions for mice by providing high quality food for longer periods, while causing less disturbance of nesting sites.

2.3 Yield Loss due to Rodent Damage

Yield is the product of all inputs used during the production period. Peter *et al.* (1988) defined yield as an interaction of assimilation rate, leaf area, duration of the grain-filling period and movable assimilates in vegetative organs available for grain production. Leaving out one of the interactions will lead to yield loss. Walker (1990) defined yield loss as a negative term and points out that yield reduction, yield gap or preventive losses are alternative terms for the same thing.

The effect of rodent attack to maize crop leads to less final crop yield (Walker, 1987). Yields of individual plants and plant populations interact to give the crop yield (Walker, 1987; 1990). Rodent damage does not necessarily result in high yield loss because sometimes at low pest population densities there is no measurable yield loss (Harris, 1974; Poché *et al.*, 1981; Arneson, 2001). Sometimes at low rodent damage maize can compasate for the rodent damage (Judenko, 1973). Judenko (1973), Hoque & Fiedler (1985) and Rubia-Sanchez *et al.* (1999) defined compensatory yield as the increase in yield of unattacked and survived plants resulting in better growth caused by reduced competition for growth resources following the death of neighbouring plants that have been attacked by rodents.

Buckle (1994) reported that in a maize field with some missing plants, the unattacked plants next to a missing plant yield more than those surrounded by other undamaged neighbour plants. This is due to reduced competition for light, water, and nutrients among maize plants in the field (Reissig *et al.*, 1985). In maize, the earlier in the crop's development the damage occurs, the greater is the time available for compensatory growth and the less the actual loss incurred. Thus, yield loss tends to have a direct relationship with the amount of damage only when that damage is inflicted on the ripening cobs (Walker, 1987; 1990). However, Myllymäki (1987), Gaunt (1990) and Buckle (1994) revealed that in maize, compensation couldn't occur if attacked or missing plants occur in large groups i.e. yield falls rapidly with increasing attack by rodents.

2.4 Rodent Outbreaks

In several localities in Tanzania, rodent outbreaks over large areas have been reported (Telford, 1989; Leirs *et al.*, 1989; Mwanjabe and Sirima, 1993; Leirs *et al.*, 1996; Mwanjabe *et al.*, 2002). Rodent outbreaks cause serious crop damage and can sometimes completely destroy maize fields before the grain is mature (Taylor, 1968; Mwanjabe *et al.*, 2002). A historical record of rodent outbreaks in Tanzania is shown in Table 1.

Table 1: Reported outbreaks of rodents in Tanzania.

Year	Rodent species involved	Region affected	References
1912	*M.natalensis*	Rombo-Kilimanjaro	Lurz (1913)
1925/26	*M.natalensis*	Morogoro	Harris (1937)
1930/31	*M.natalensis*	Morogoro	Harris (1937)
1936	*M.natalensis*	Lindi	Kingdon (1974)
1951/52	*M.natalensis*	Pare-Kilimanjaro	Heisch *et al.*, (1953), Taylor (1968)
1955/56	*M.natalensis*	Dodoma & Tabora	Chapman *et al.*, (1959), Kingdon, (1974)
1962/63	*M.natalensis, A. niloticus, Rhabdomys pumilo*	Shinyanga, Arusha, Singida	Taylor (1963, 1968), Taylor and Green (1974)
1971	*M.natalensis*	Lindi	Kingdon (1974)
1974	*M.natalensis*	Shinyanga, Tabora	Mkondya (1977)
1975	*M.natalensis*	Tanga, Tabora, Morogoro & Mbeya	Kilonzo and Mtoi (1975), Mkondya (1977)
1978	*M.natalensis*	Lushoto-Tanga	Kilonzo (1979)
1980	*M.natalensis*	Doma-Morogoro	Kilonzo (1980)
1983/84	*M.natalensis*	Morogoro, Kigoma, Tabora & Mbeya	Telford (1989) and Kilonzo (1983)
1989/90	*M.natalensis*	Morogoro, Lindi	Mwanjabe (1990-1992)
1997/98	*M.natalensis*	Morogoro, Coastal region, and Tanga	Mwanjabe (1998)
2001	*M.natalensis, A. niloticus*	Morogoro, Lindi, Arusha, Tabora	Ministry of Agriculture and Food (2001)

In years with small rodent outbreaks, damage to agricultural crops may still be considerable (Fiedler, 1988; Parshad *et al.*, 1989). The occurrence of rodent outreaks in Tanzania is influenced by the rainfall pattern. In Morogoro, Tanzania, rodents breed during the long rains (March – May) and usually starts in April (one month after the usual peak rainfall), lasting until September (Leirs, 1995). New-borns grow slowly and normally do not mature before the next rainy period. Unless abundant rains appear before March and April the following year, they will be at least six months old before they begin to breed (Leirs, 1995). However, if the short rains are abundant, sub-adults mature and may breed as early as January. Young born in such early breeding seasons grow fast and mature in their third month, starting to breed during the main breeding period. This additional generation allows the development of high densities later in the year. In fact, unusual abundant rainfall during the first month of the rainy season is a reliable predictor for the occurrence of an outbreak in the following year (Leirs *et al.*, 1996).

Females of *M. natalensis* may reproduce on average five to six times a year, each consisting of around 11 young per litter (Reissig *et al.*, 1985 and Leirs, 1994; 1995). *Mastomys natalensis* is very prolific having up to 24 young in one litter (Fiedler, 1988) and breeding at intervals of 25 days or less (Leirs, 1994 & 1995). Population explosions of this species happen at irregular intervals (Leirs *et al.*, 1996).

Telford (1989) reported that the maximum density of *M. natalensis* in Morogoro was 1125 animals per hectare in October. Mwanjabe (1993) reported that, populations of *M. natalensis* undergo irregular population explosions with densities as high as 1000 rats ha^{-1}. In Coast, Lindi and Mtwara regions, outbreaks of *M. natalensis* reach densities of between 200 – 800 rats ha^{-1} (Mwanjabe and Sirima, 1993). However, in normal circumstances, 200 rats ha^{-1} is a normal population density at Morogoro (Leirs, 1994).

2.5 Sampling Techniques for Rodent Damage

Planning a scheme for sampling of crop damage is usually a two step process (Rennison and Buckle, 1988). The first stage is to choose a suitable sampling plan. The next step is to plan how to take the sample so that it conforms with the requirements of the sampling plan (Buckle and Rowe, 1981). The objective of the planning should always be to combine the two components of the scheme to produce results that will be either more or less accurate than required. Sampling technique should focus on the damage distribution in the field. For example, in situations where rodent damage is randomly distributed, non-stratified simple random sampling technique could be used. However, non-stratified simple random sampling technique is not a practical method for sampling densely planted crops from which it is impractical to draw samples of individuals (Rennison and Buckle, 1988). This method therefore, need randomization which requires beforehand knowledge of number of plants per unit area and their spacing pattern.

Non-stratified systematic-z-sampling measures damage that is stratified parallel to field edges more accurately than non-stratified simple random samples (Rennison and Buckle, 1988). However, in situations where the spatial damage distribution is either regular or random this method could not improve the estimates

Non-stratified systematic row sampling tends to spread the sampling more evenly through the population than either non stratified simple random sampling or non-stratified systematic-z-sampling does, and the results are consequently more accurate. However, there are disadvantages if the population contains a periodic type of variation and the sampling interval happens to coincide with it, in which case the sample will be badly biased. Secondly, there is often no reliable method of estimating the standard error of the sample mean (Rennison and Buckle, 1988). Therefore, this method should be used with care and forethought.

In some situations the variability can be reduced without introducing bias by using other information about the damage distribution. Stratified sampling is therefore used in fields where rodent damage is heterogeneous in different parts, hence, estimates are made separately in each of these parts. This is not uncommon when areas of cultivation are bounded on one or more sides by uncultivated land which is a refuge and habitat for the rodent species. In such situations damage is often more intense on the edges of cultivated areas than at the centre. Benigno (1979) recorded this frequently in the case of rodent damage in maize and also, but less frequently, in rice. Cases have also been recorded of rodent damage to rice being much more intense at the centers of fields than at the edges.

Rennison and Buckle (1988) reviewed several sampling techniques for damage and yield loss assessment including simple random, cluster, stratified, diagonal, systematic, and multiple-stage sampling. The authors found that in a maize field, simple random, stratified and systematic sampling techniques can be used because they are less time consuming and give more reliable estimates of damage and yield loss than other sampling techniques. Hoque *et al.* (1986) reported that strip (2 rows by 5 holes) systematic sampling technique, when compared with simple random and random quadrat in maize fields during ripening time, gave estimates that were closest to the actual damage and yield loss and was least time consuming. However, the authors did not compare these sampling techniques for other growth stages (e.g. at planting and seedling stage) and in different cropping patterns.

USAID (1983) evaluated three sampling techniques used in maize crop, vz. random sampling of 50 hills in 50 rows, systematic strip sampling of 1 * 5 hills and stratified quadrat sampling of 5 * 5 hill quadrats randomly located within three strata. It was found that systematic strip method was the fastest. The other methods took longer to complete data sheets (row counts, number of randomly selected ears, transcribe data) and to examine ears. It was further reported that random and systematic strip methods underestimate actual damage because maize fields usually show clumped, peripheral rat damage. Therefore, a method incorporating stratification with a larger proportion of samples in outer rows and quadrats to account for clumping is preferable (USAID, 1983).

Key (1990) used transects of 50 planted points within a maize field to estimate rodent damage to maize at seedling, and rodent cob damages at maturity stages. In Tanzania, some damage quantification was reported by Taylor (1968), Mkondya (1977) and Myllymäki (1987). However, the sampling techniques used were not stated. Mwanjabe and Leirs (1997) used systematic sampling technique to evaluate maize damage at seedling stage but not damage at maturity stage. In both sampling techniques, sampling was restricted to the inner field areas to reduce inter field effects and prevent sampling of abnormal rodent movement behaviour in relation to barriers (Kaukeinen, 1984). This indicates that when crop field edges (although convenient) are sampled, they may be unrepresentative of rodent damage (Kaukeinen, 1984). Knowledge on which techniques are most reliable and cost effective in determining the damage and yield loss in maize fields is considered important in relation to changing rodent densities.

2.6 Modelling Rodent Outbreaks

Leirs *et al.* (1996; 1997a) developed prediction models for outbreaks of *M. natalensis* in Tanzania (Appendix 3). The authors found that rodent population density explosions depend largely on rainfall, but the demographic processes are also density-dependent. This information allowed developing models that can simulate population dynamics and predict future population size (Fig. 2). However, the model does not predict the extent of crop damage and yield loss associated with the predicted rodent density.

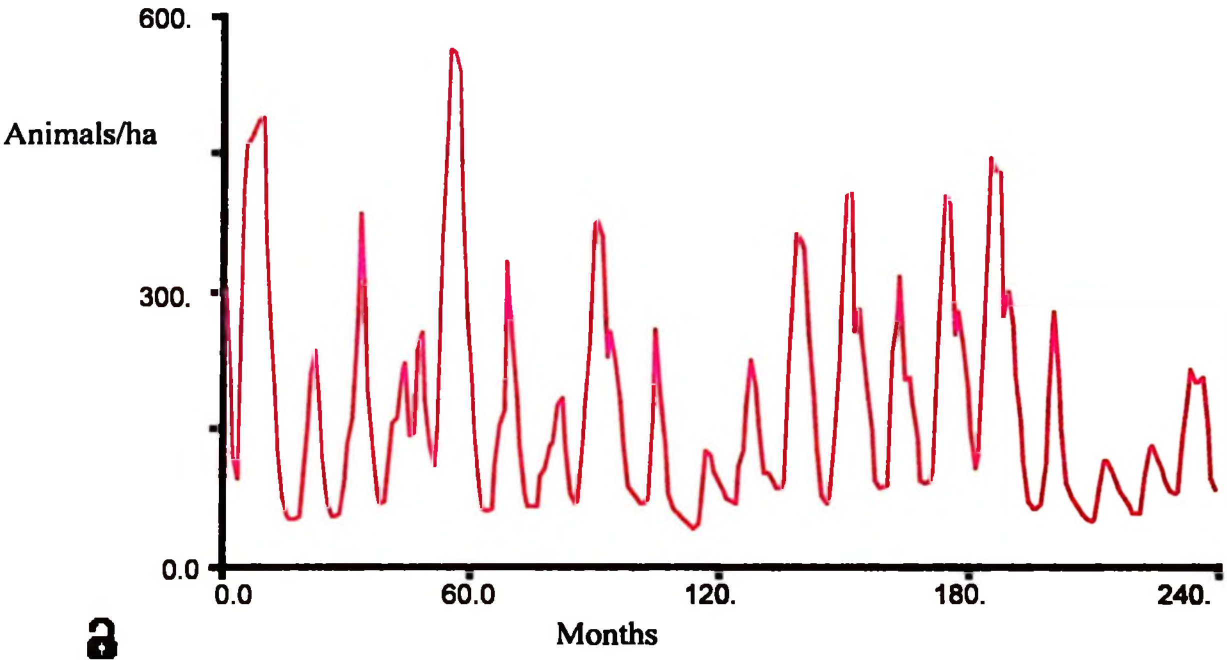


Figure 2: Simulation model of the population dynamics of *Mastomys natalensi* (After Leirs, 1996,1997a)

Prediction of crop loss due to rodents is necessary in order to: set priorities, to quantify the efficiency of farmer's current rodent management practices, develop policies at local/region levels, establish the need for future research in the context of agricultural changes. The understanding of the relationship between damage, yield loss and variations in rodent density requires a comprehensive study. These relationships can be incorporated in population models, for prediction of both *M. natalensis* population explosion, damage and yield loss.

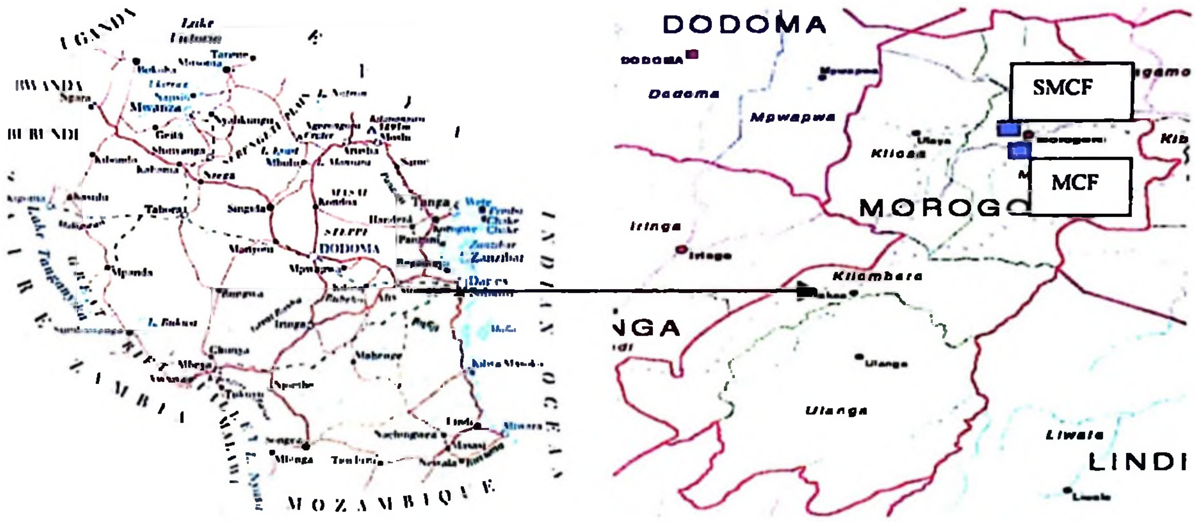
CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Location and Seasons

The study was conducted at two sites at the Sokoine University of Agriculture (SUA) Morogoro, Tanzania (Fig. 3). Field experiments at the SUA Main Campus were laid out in the University farm, situated 4 km from Morogoro municipality at latitude $6^0 50'$S and longitude $37^0 38'$E and an altitude of 510 m above sea level (a.s.l.). The soils in the study area have been derived from alluvial materials from the Uluguru mountains (Kesseba *et al.*, 1972). The study area is covered by reddish and reddish brown soils (Sampson & Wright, 1964). The local vegetation is mainly grassland dominated by *Andropogon* spp., *Hyperrhenia* spp., and *Themeda* spp., *Panicum hanningtonii*, *Rothboellia conchinchinensis*, *Pennisetum polystachyon* and *Cymbopogon* sp. Scattered kapok trees (*Ceiba pentandra* Gaertn.) and *Acacia* spp. are the most common trees in the area.

Field experiments at Solomon Mahlangu Campus were laid out in a farm situated at 480 m a.s.l. at latitude $6^0 46'$S and longitude $37^0 37'$E. The local vegetation is mainly grassland dominated by *Echinochloa colona*, *Panicum* spp., and *Sorghum arundinaceum*. The study fields were being used for studies on aspects of rodent population biology. The experiments were conducted during the long and short rain seasons in 1999 and 2000. In 2001, the studies were conducted during the long rain season only.



(a) (b)

Figure 3: Map of: a = Tanzania, and b = Morogoro region showing location of study sites; MCF = Main Campus farm, and SMCF = Solomon Mahlangu Campus farm.

3.2 Weather Conditions

Meteorological data were obtained from the SUA Main Campus Meteorological Station. The study sites have bimodal rainfall pattern. The short rains are received between October and December and long rains between March and June. The maize crop was cultivated during both short and long rain seasons at Solomon Mahlangu Campus. At the Main Campus farm, maize cultivation was done during the long rains season only.

Data on total rainfall, mean temperature (both maximum and minimum temperatures), mean radiation, and total pan evaporation in 1999, 2000 and 2001 are given in Appendix 4. The total annual rainfall was 836.5, 790.0, and 784.0 mm in 1999, 2000 and 2001, respectively. The short rains were generally low and intermittent. In 1999 (for both long and short rains) and 2000 (for long rains), rainfall was normal at the two study sites and the crop was realised. High and unseasonal rains were experienced during the short rains in December 2000, and January - February 2001. At Solomon Mahlangu Campus, soil moisture content was above field capacity (water lodging) which affected the performance of the crop, particularly seed germination. At both sites rainfall ended early in May 2001 before the maize crop matured.

During the three years of study, the maximum temperature recorded was 33.8^0C in February 1999, while the minimum temperature was 15.7^0C, in July 2001. The mean radiation was generally higher for the short than for the long rain seasons. The total pan evaporation for both experimental years were 1523.6, 1871.6, and 1751.5 mm/m^2 for 1999, 2000, and 2001, respectively.

3.3 Experimental Fields

The studies were conducted in 21 experimental fields, 70 x 70 m each (approximately 0.5 ha). The field size (0.5 ha) corresponds to smallholder farm size in Tanzania. The plots were located a minimum of 80 m and maximum of 300 m apart. For those fields which were 80 m apart, some were enclosed. Therefore, in all fields the populations of rodents were independent. The experimental fields had different treatments including manipulating the level of predation, dispersal, land management practices and intercropping system (mono or intercropping). Four fields were fenced. The different treatments provided a range of rodent densities in the fields. The description of the fields is provided in Table 2.

Table 2: Description experimental plots

Description of fields (treatment)	No. of fields used
Mosaic fields: fields planted with maize and surrounded by fallow land (i.e. CO1, CO10, Mosa13, Mosa26, DM1, and DM2)	6
Fields planted with maize, enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (i.e. CE5, and CE9)	2
Fields planted with maize, enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (i.e. NE3, and NE8)	2
Fields planted with maize, but open with perches for attraction of predatory birds (i.e. PR2, and PR7)	2
Fields planted with maize and enclosed by chicken mesh and covered by nets (i.e. NO4, and NO6)	2
Fields planted with maize and surrounded by other cultivated maize fields (i.e. Monoculture)	1
Fields planted with maize only and land prepared by slash and burn (mono-crop) (i.e. SM3, and SM4)	2
Fields planted with maize and beans (inter-cropped) and land prepared by slash and burn (i.e. SI7, and SI8)	2
Fields planted with maize and beans (inter-cropped) and land prepared by tractor (i.e. DI5, and DI6)	2

3.4 Soil Characteristics in Experimental Fields

Soil properties have an effect on crop performance and therefore, the soils were analysed to establish their properties before applying fertilizer. In the first year of study, soil samples were taken from a depth of 0 - 20 cm, which is the normal ploughing depth. Eight samples were taken from each field. Samples were mixed thoroughly for uniformity and were used for analysing the soil physical and chemical characteristics. Soil texture was determined by the hydrometer method described by Gee and Bauder (1986). The following methods were used to ascertain the presence and concentration of minerals.

i) Exchangeable potassium was determined on a 1N NH_4OH leachate by flame photometry (Maclean, 1982)

ii) Extractable Phosphorus was extracted with Bray and Kurtz solution and the quantity determined by the Molybdenum Blue method (Bray and Kurtz, 1945)

iii) Total Nitrogen was determined by Kjeldal method (Bremner and Mulvaney, 1982).

iv) pH values were determined in a 1:2 soil water suspension using the glass electrode assembly according to Mclean (1982)

v) Soluble sulphur ($So_4^{=}$) was determined by spectrophotometer method (Landon, 1991)

In the study sites, the soil particle analysis indicated that, the top soils (0-20 cm deep) varied from clay, sandy clay to sandy clay loam at the Main Campus Farm and sandy clay, sandy clay loam to sandy loam soils at Solomon Mahlangu Campus.

The chemical analysis in both farms showed that pH values were in a range where greatest number of mineral elements was available for maize plants uptake. The values were at medium level (Landon, 1991). However, the percentage total nitrogen, extractable phosphorus, and soluble sulphur ($So_4^{=}$) were low in the two sites compared with the recommended amount for maize production in Morogoro, viz: 0.2 - 0.5%; 25 ppm; and 6 - 12 ppm, respectively (Landon, 1991). The level of exchangeable potassium in all fields and locations was high compared to recommended level of 0.2 - 0.6 milliequivalent (me)/100g of soil (Landon, 1991). Therefore, this element is not a limiting factor for maize growth and production in the study sites. Table 3 shows the general characteristics of the soils in the two study sites.

Table 3: The soil characteristics of experimental fields*

Field	Mechanical analysis				Chemical analysis				
	%clay	%Silt	%sand	Textural Class	Soil pH (1:2.5) H_2O	H_2O soluble $SO_4^=$ (ppm)	TN (%)	Extract Br 1-P (ppm)	Exch. K+ (me/100g)
CO1	35	15	50	Sandy clay	6.71	4.38	0.11	4.41	1.057
PR2	51	11	38	Clay	5.63	3.89	0.09	1.97	1.231
NE3	49	11	40	Clay	5.63	1.75	0.14	1.41	1.190
NO4	55	11	34	Clay	6.02	1.75	0.12	1.58	1.211
CE5	53	9	38	Clay	6.08	1.75	0.13	3.19	1.785
NO6	53	13	34	Clay	6.06	2.88	0.13	1.97	2.086
PR7	45	13	42	Clay	6.53	1.25	0.11	2.44	2.129
NE8	45	11	44	Clay	6.69	3.38	0.12	2.72	1.914
CE9	33	17	50	Sandy clay loam	7.04	1.75	0.10	2.91	1.807
CO10	41	11	48	Sand y clay	6.90	2.88	0.11	1.24	2.108
Mosa13	57	9	34	Clay	5.87	3.38	0.11	1.41	1.375
Mosa26	47	15	38	Clay	6.60	1.75	0.11	4.97	1.850
Mono	49	15	36	Clay	6.36	2.25	0.13	2.72	2.065
SM3	39	10	51	Sandy clay	6.34	2.50	0.08	7.79	0.878
DI5	24	10	66	Sandy clay loam	6.20	2.82	0.06	6.95	0.469
DI6	23	9	69	Sandy loam	6.47	1.91	0.06	17.96	0.369
DM1	16	8	76	Sandy loam	6.20	1.96	0.06	14.9	0.35
DM2	36	10	55	Sandy clay	6.49	3.19	0.08	6.95	0.531
SM4	25	9	67	Sandy clay loam	7.18	7.75	0.05	12.27	1.284
SI7	34	12	53	Sandy clay	6.98	1.25	0.08	15.86	0.605
SI8	34	12	55	Sandy clay	6.78	2.19	0.08	4.66	0.614

*Analysis was done in the laboratories of the Department of Soil Science, Sokoine University of Agriculture. H_2O soluble $SO_4^=$ (ppm) = Soluble sulphur; TN (%) = Total nitrogen; Extract Br 1-P (ppm) = Extractable phosphorus; Exch. K^+ (me/100g) = Exchangeable potassium.

3.5 Agronomic Practices

After the onset of long rains in February to March and short rains in October to November, fields were ploughed and prepared for planting. Planting of maize took place in March for the long rains and late October or early November in the short rains season each year. The exact timing of damage obcervations depended on the date of sowing, which was in turn dependent on the onset of rainfall. All fields were treated in a standard way:

- ploughed early,
- application of Triple Super Phosphate (TSP) fertilizer at a rate of 20 kg P_20_5/ha before planting and
- application of nitrogen fertilizer in the form of uUrea at the rate of 40 kg N/ha twice as a top dressing at 3 weeks after sowing and at booting stage (i.e. this was based on the results of soil analysis in section 3.4 above).
- Three seeds per hole, planting space of 90 cm x 60 cm (Plate 6) and the same maize variety, Staha, were used as a standard.
- Weeding was carried out twice. Harvesting was carried out by hand picking of the cobs when all cob silks were dry in late July to early August for the long rains crop.

No yields were realized in the short rains season. Therefore, only damage estimates at planting were recorded during the short rains season.

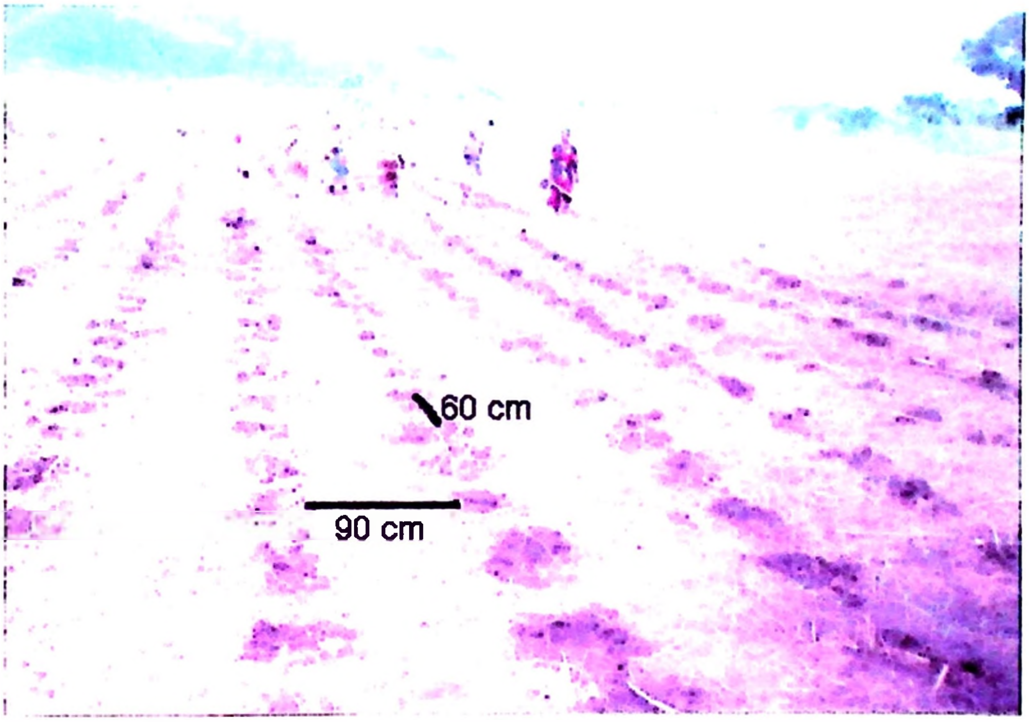


Plate 6: Planting maize seeds in one of the slash and burn experimental fields at Solomon Mahlangu Campus study site.

3.6 Sampling Procedures

Since the study fields were subjected to different treatments, it was expected that the distribution of damage within fields would be highly variable. Four sampling techniques for comparison in order to choose the best performing in terms of time, complexity and reliability were used. These four sampling techniques were found in literature as described in 3.6.1- 4 sections. One sampling technique (Non-stratified systematic row sampling technique) is commonly used in Tanzania while the others are commonly used elsewhere.

Stratified sampling technique is used in fields where rat damage is heterogeneous (i.e. not randomly distributed but higher in some zones than in others). Estimates are made separately in each of these zones and are combined taking the relative size of each strata into account. One goal of stratification is to create sub-universes that are uniform internally, i.e. to minimize variation within strata and maximize variation among strata (Cochran, 1977). Stratification was adapted in the current study because the fields were bounded by uncultivated fallow land, which was a refugium for *M. natalensis*. Three strata were taken as described in 3.6.2 below.

Four techniques (viz. Stratified random square sampling, non-stratified simple random sampling, non-stratified systematic z sampling, and non-stratified systematic row sampling) were compared in terms of time, accuracy and precision. Throughout the study period, crop damage assessment was carried out at seedling stage (10 days after planting) because seeds and seedlings removal is most serious 4 - 8 days after planting. At maturity, rodent damage assessment was done one week before harvesting. Rodent damage to maize in the field was measured at two stages, viz. At seedling and from ripening to maturity stage of maize cobs. At seedling stage, missing seeds and seedlings were recorded at each sampled planting hole. Missing seedlings (i.e. removed by rodents) were not remedied by replanting. The ongoing capture-recapture studies showed that more than 97% of the rodent species in the fields were *M. natalensis* (Massawe, 2003). Two other species of rodents (*Tatera sp*, and *Lemniscomys sp*) were captured at the SUA Main Campus study site (Vibe-Petersen, 2003). *Tatera sp*, and *Mus sp* were captured at Solomon Mahlangu Campus (Massawe, 2003). *Thryonomys sp* were present in the fields at Solomon Mahlangu Campus shown by the characteristic oblong faecal droppings containing indigested plant shafts. Damage estimates at the seedling crop growth stage were based on two assumptions: first, the germination capacity of maize seeds is 100% and secondly, other factors are constant; therefore, only rodents caused damage to maize seedlings.

In the two years of study, actual damage was established at the seedling and maturity stages of maize using four sampling techniques. The robustness of the sampling methods was compared. At seedling stage, actual damage was recorded in 15 fields (two fields in 1999, thirteen in 2000) at the Main Campus Farm. In the remaining fields, only non-stratified systematic row sampling was used for damage estimates.

In eight fields at the Solomon Mahlangu Campus farm, in both study years, only non-stratified systematic row sampling (see below) was used at the seedling stage. Actual counting of all cobs per field was employed at maturity stage because maize cobs in this farm were damaged by rodents in the second year of the study. At this stage, the damaged proportion of each cob was estimated as described in section 3.7 (b). Damage of cobs was assumed to be due to *M. natalensis* for upright maize plants because these rodents are able to climb the stalk (Fiedler, 1988). However, rodent species could also have been responsible for the damage on fallen maize plants.

The four sampling techniques used in this study have been used in other countries, especially in South Asia, in maize and rice fields (Benigno, 1979; Benigno, 1980; Hoque *et al.*, 1986; Rennison and Buckle, 1988;) and in Africa (Mwanjabe & Leirs, 1997). Based on the results of the first and second years of study, non-stratified systematic sampling was adopted as a standard sampling technique in all the fields during the third year (results section).

Non-stratified systematic row sampling technique was used to establish the relationship between rodent damage, yield loss and rodent density at planting and harvest time. Rodent population size in each field was estimated by closed-model Capture-Mark-Recapture (CMR) (estimator Mh in CAPTURE) (White *et al.*, 1982) based on sessions of three consecutive trapping nights. The population size was estimated prior to ploughing and after planting. The mean value of the estimates was used as a measure of rodent density at planting in each plot. The mean rodent density for each of the three months was used to establish the relationship between population density, damage at planting, and the resultant yield loss at harvest.

The relationship between yield loss (kg) and rodent density at ripening stage was also established. The mean density for each of the three months (i.e. June, July and August) was taken. This is due to the reason that maize damage by rodents occurs as soon as grain filling begins (milky stage) in June until harvesting in August.

Rodent population estimates are important to assess the economic loss and to evaluate the success of control measures (Judenko, 1973; Yashoda *et al.*, 1979). In order to establish the model that fits best, the data points were plotted as scatter diagrams to determine the type of function (Harshbarger and Reynolds, 2000). Fitting of the curve was done using computer software (SigmaPlot, Excel, and Table curve 2D). To establish the type of model that fitted the data best, several criteria were combined. These included Akaike Information Criteria (Akaike, 1973), Bayesian Information Criteria (Schwarz, 1978), Hannan and Quinn (Hannan and Quinn, 1979) and Minimum Description Length (Rissanan, 1996). Akaike's Information Criteria (AIC) (Akaike, 1973, 1974, 1980 & 1987) were determined from several models and were compared. The AIC value closer to zero (i.e. a model is selected if the value of AIC is minimal in relation to other models) indicates good fit and greater parsimony (Akaike, 1974; Hair *et al.*, 1998). The general form for calculating AIC is:

$$AIC = -2*LN(likelihood) + 2*K \qquad [1]$$

where

LN is the natural logarithm;

k is the number of estimatable parameters in the model

The AIC can also be calculated using residual sums of squares from regression analysis (Burnham and Anderson, 1998, Anderson and Burnham, 1999):

$$AIC = n*LN(RSS/n) + 2*K \quad [2]$$

where

n is the number of data points (observations)

RSS is the residual sum of squares i.e. $\sum(\text{observed - predicted})^2$.

However, AIC requires a bias-adjustment for small sample size. As B&A rule of thumb: If the ratio of n/K< 40, then a bias-adjustment is used (Akaike, 1987; Royal, 1997; Burnham and Anderson, 1998):

$$AIC = n*LN(RSS/n) + 2*K + (2*K*(K+1))/(n-K-1) \quad [3]$$

where variables are as defined above. This formula was used in this study because the ratio of n/K was less than 40 for all relationships established. Therefore, among the models determined, the one with less AIC was taken as the most parsimonious model for the data (Akaike, 1974, 1987). The first top models were accepted as not significantly different if the difference in their AIC < 2. The appropriate model was selected based on some biological facts such as germination rate failure (i.e. it should not be > 15%).

3.6.1 Non - stratified systematic row sampling:

A start is made at a fixed point near the beginning of the rows after which every n^{th} row is included in the sample. The value of n is taken so as to spread the units evenly over the population. In this study, the systematic sampling technique was based on one used by Mwanjabe and Leirs (1997) in which the sampling unit is a maize row; four rows apart and leaving out the two outer rows (Fig. 4) in order to reduce inter field effects and prevent sampling of abnormal rodent movement behaviour in relation to barriers (Kaukeinen, 1984). The assessor walks along maize rows across the field, counting seedlings at each hole in the row. In each field, 15 rows were sampled.

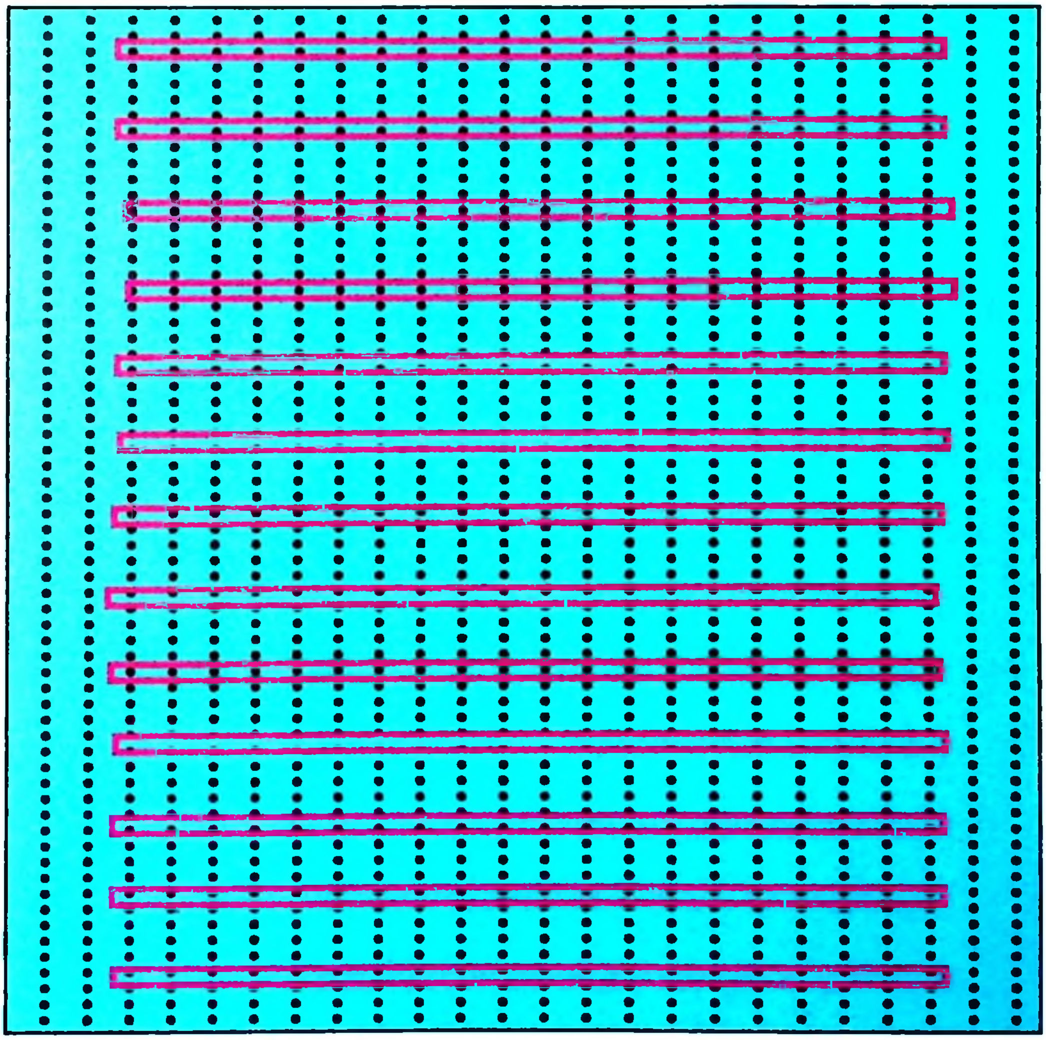


Figure 4: Sketch of Non - stratified systematic row sampling

3.6.2 Stratified random square sampling:

The fields were surveyed superficially in order to visualize the distribution of rat damage. Sections of the fields with relatively similar damage intensity (which was one common characteristic of interest i.e. damage level) were grouped in strata either as low (L), median (M) or high (H) damage (Fig. 5) based on the ratings of 0-25% as low damaged areas, 26-50% as medium, and over 50% as high rodent damage. Within each stratum, 5 rows * 5 holes (square) were selected randomly in an area of similar damage intensity. Three sampling units were selected per stratum per field. The mean percentage damage was calculated for the whole field based on the proportion of damage for each stratum. The proportional contribution of each stratum in the field was determined by visual estimates of how much the stratum occupy per field. The reliability of this proportion was dependent on the assessor, which was not constant from one field to another and year to year even in the same field.

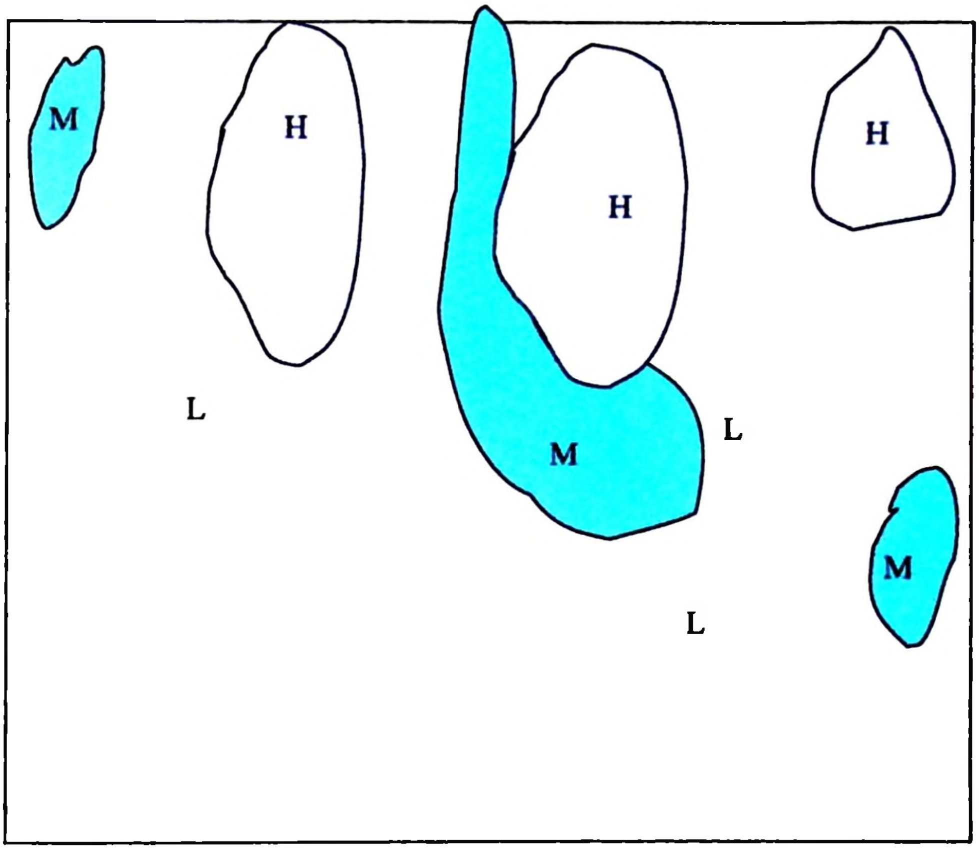


Figure 5: Sketch of stratified random square sampling technique with three strata (L = low damage, M = medium damage, and H = high damage).

3.6.3 Non-stratified systematic z sampling:

Samples were taken systematically from nine points (2 rows by 5 holes) at fixed distances along a zigzag line in the maize field running along two sides of the field and connected by a diagonal line. A total of 90 holes (270 plants) were examined per field. The distance between any two sampling points on the parallel lines was 27.5 m, while that between points on the diagonal line was 21.0 m (Fig.6). All nine points formed one sample. Such sampling technique can account for random, regular, or aggregate rodent damage distributions in a field (Lin *et al.*, 1979).

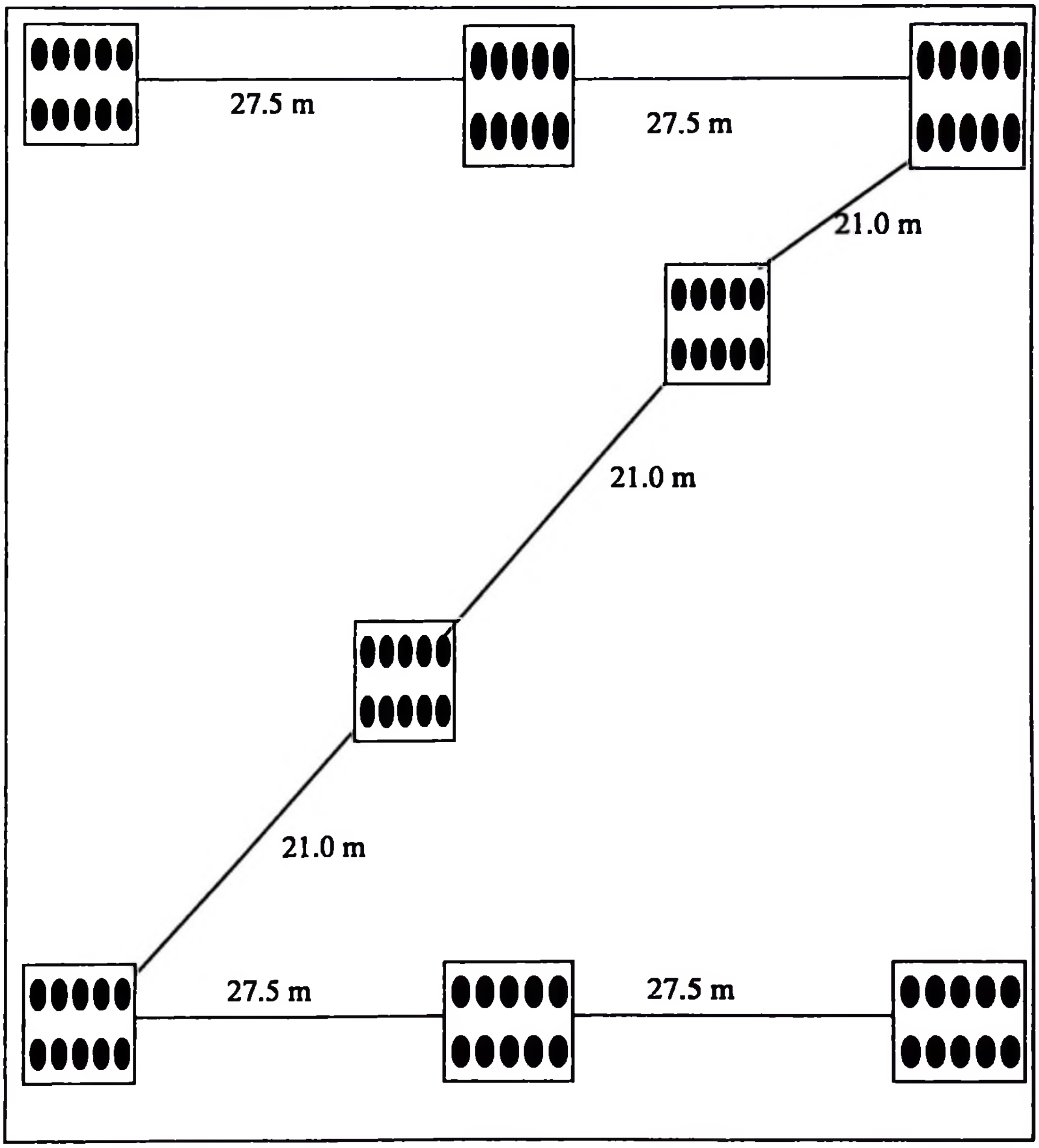


Figure 6: Sketch of non-stratified systematic z sampling technique. Each quadrat has 2 rows with 5 holes in a row

3.6.4 Non-stratified simple random sampling,

Each sample unit (a plant hole) was drawn independently and with equal probability from the population under investigation using random-pair technique (Gomez and Gomez, 1984). The total number of rows per field and holes per row was determined, leaving out two rows out around each field (e.g. 75 rows per field and 114 holes per row). A total of 120 pairs of random numbers were selected and they formed the co-ordinates of the sampling points in the field. Figure 7 shows a hypothetical field with 10 rows and 20 holes assigned random numbers. The damage estimate was obtained by using the formula in section 3.7 (a).

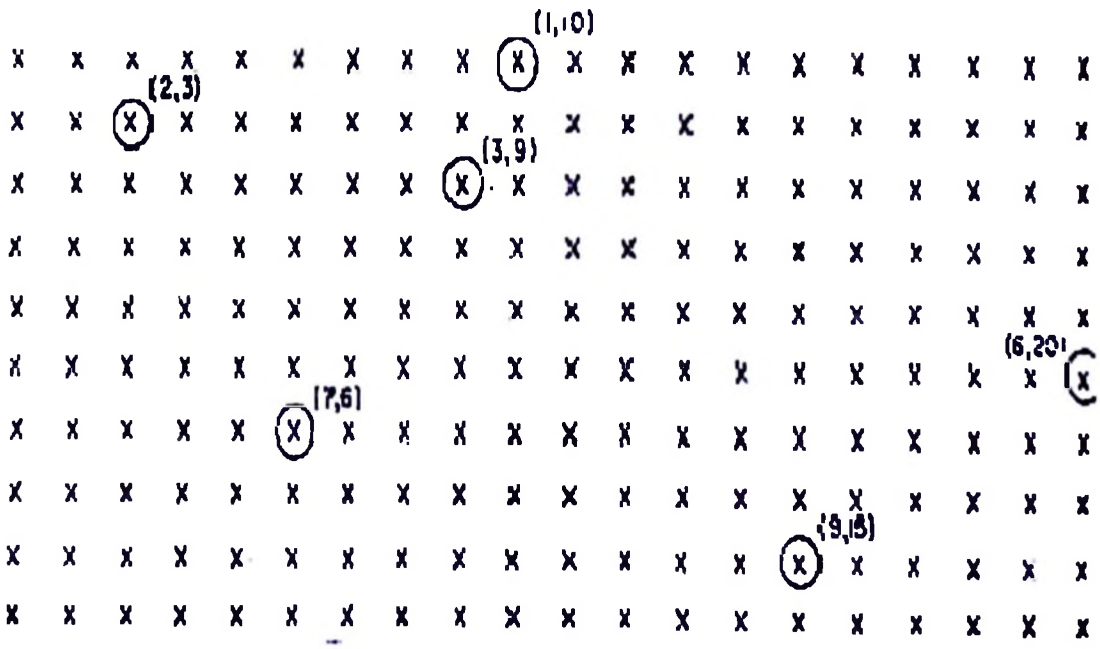


Figure 7: A hypothetical sketch of map for non stratified simple random technique showing six randomly selected sample holes using the random-pair technique, for a plot consisting of 10 rows (vertical, left to right) and 20 holes per row (horizontal). (Adopted from Gomez and Gomez, 1984).

3.7 Estimates of Damage

In all the fields, the percentage damage at two cropg rowth stages was determined as follows:

(a) At planting or seedling stage,

Since three seeds had been planted per hole, the difference between observed and expected number of seedlings was used to calculate the percentage damage using the formula:

$$D = 100*d/(u + d) \quad [4]$$

where:

D = percentage damage

d = missing seedlings or plants and

u = total number of seedlings not missing

(b) At ear ripening stage: The ears were examined for damage by rodents on upright, leaning, and fallen maize stems. Two types of damage were assessed; namely longitudinal and circular ear damage. Longitudinal ear damage occurred when missing kernels were along the length of the ear. In circular ear damage, missing kernels were in a ring form around the ear. Measurements taken on each damaged ear were the length of ear, length of damaged portion and circumference of damaged portion for circular damage. For both types of cob damage, the proportion damaged was calculated (see Appendix 5 for more detail). The damaged proportion (cm) of cobs per field was calculated as the ratio of the total damaged portions and the number of ears per sample in that field.

3.8 Yield Loss

Individual fields were harvested and the ears were put in bags and stored separately. The cobs were threshed manually, cleaned thoroughly by hand winnowing, sun dried for 3 - 4 days and weighed. Grain moisture content (measured with an Electronic Moisture Meter) was adjusted to a common moisture of 15.5% (Bessin and Martin, 1997; Moyal, 1998) in order to maintain uniformity for all the fields. The following formula was used:

$$Y = [(100 - k)/(100 - 15.5)] * J \qquad [5]$$

where:

Y = adjusted weight of the sample at 15.5% moisture content,

k = moisture content of the sample, and

J = weight of the sample.

The potential yield in absence of rodent damage (W_0) was calculated as follows:

$$W_0 = a_0 T \qquad [6]$$

where:

a_0 = mean actual yield of unattacked plant in kg (i.e. calculated as the average yield for all plants that were completely free of rodent damage, i.e. plants which at harvest time were still standing with three plants in a hole and without any damage of the cobs; neighbouring holes may or may not have been attacked),

T = Total number of seeds planted, assuming a 100% germination rate.

Since rodents may cause damage not only at planting, but also when the crop is ripening and at maturity, one can also calculate the yield loss given the damage of cobs at harvest time (LOS_R). Cob damage by rodents is characteristically different from that of other pests (such as birds, ants). First, the mean yield loss per damaged cob ($\acute{Y}$) was calculated. In some fields, few cobs were damaged by rodents and therefore, ten rodent damaged per cobs were selected randomly, threshed and weighed. The mean damage/cob was calculated. The mean yield loss ($\acute{Y}$) was obtained from the difference between mean yields of undamaged and damaged cobs. Yield loss due to rodents (LOS_R) was computed as:

$LOS_R = \acute{Y} * T$..[7]

where:

LOS_R = grain loss (kg)

$\acute{Y}$ = mean loss/damaged cob (kg)

T = Total damaged cobs in a sample

The total yield loss (LOS_T) is calculated as:

$LOS_T = W_0 - ACT$ ....[8]

Therefore, LOS_T, can be divided into: (i) cobs damage (LOS_R), and (ii) the yield loss due to rodent attack at seedling stage (LOS_p):

Therefore,

$LOS_p = LOS_T - LOS_R$ ....[9]

3.9 Data Analysis

3.9.1 Determination of rodent damage distribution pattern

Patterns of distribution of rodent damage in field crops show a strong edge effect in many situations (Taylor, 1972) and this was examined. "Edge" has been defined as an area of potential refuge such as a perimeter fence, a terrace bank or a patch of fallow land (Key, 1990). The rodent damage data (from the fields in which actual damage at seedling was determined) were used to determine damage distribution and to establish the variance-to-mean ratio (s^2/mean). The variance to mean ratio was calculated as the coeffient of Dispersion (CD) shown in equation 10

$$CD = \frac{s^2}{\bar{x}} = \frac{\frac{\sum \left(x - \bar{x} \right)^2}{n - 1}}{\frac{\left(\sum x \right)}{n}}$$

....[10]

The distribution of rodent damage in a field is either random, aggregate, or regular (Kranz, 1993). A variance-to-mean ratio in the range 0.7 - 1.3 was considered to represent random distribution of rodent damage. Damage range greater than 1.3 was aggregate (clustered) and a range less than 0.7 was considered regular. When variance to mean ratio is large, the variation of damage distribution in the field increases and becomes aggregate. A small variance to mean ratio indicates a regular damage distribution. The damage in the fields was illustrated diagramatically for each type of distribution. Only rows of 3,8,13,.,.,., 57,63,.,., were used for this illustration, although damage was assessed in all the rows.

3.9.2 Evaluation of estimation techniques

3.9.2.1 Comparison between techniques:

The two most important factors influencing decision in selecting sampling methods are reliability and costs. Reliability of the estimated damage and yield loss increase as the sample size increases but, obviously, cost is the limiting factor. Thus, we have to define the proper balance between the reliability of the estimate and the cost of obtaining it. Costs can be expressed in terms of human hours required to collect samples, time taken for visual inspection of the collected samples and time for identification and counting the damaged and undamaged seedlings in a maize crop. In the current study, the sampling techniques were compared in terms of:

3.9.2.1.1 Time consumption

The time spent to estimate per sampling technique in each field was recorded and compared between different sampling techniques.

3.9.2.1.2 Complexity

Complexity was based on workability (i.e. if the technique is difficult to apply or not). Four ratings were used for complexity:

Very simple = no training; no special equipment are required,

Simple = little training is required; no special equipment required,

Complex = training is required eg. measuring the length and width of a quadrat and the distance between the two sample points. Special equipment is required (eg. tape measure).

Highly complex = special training is necessary in terms of field work and knowledge of statistics. Also, it is difficult to interpret and define the technique.

3.9.2.1.3 Reliability

All four techniques were evaluated for reliability using two statistical criteria.

(i) Correlation between damage estimate with actual damage at planting and maturity

Damage estimates at seedling and maturity stages were correlated with the actual damage. This was done in order to establish the closeness between the estimated and actual damage using all four sampling techniques. The technique with highest correlation coefficient was considered the best.

(ii) Correlation between damage estimate and yield loss at harvest.

Damage and yield loss estimates due to attack of seedlings in each field were subjected to correlation analysis. The technique with high correlation coefficient was considered the best for predicting yield loss.

3.9.2.2 Sampling intensity:

Since the non-stratified systematic row sampling technique performed best (Results section) further investigations on which sampling row interval at planting time would give an optimal balance between effort and accuracy were conducted. For this work, simulation of sampling intensities and re-sampling data from the fifteen fields for which actual damage was recorded were carried out. Different sampling intervals (every 2nd, 3rd, 4th, 5th, ...20th row) were chosen and for each sampling interval, all possible simulations were run by choosing a different starting line every time. Obviously, choosing every single line corresponds to counting all plants (i.e. the actual damage).

The variation between estimates was plotted against sampling interval. Simulations were run for each of the 15 fields for which actual damage was recorded. The same was repeated for the non-stratified simple random sampling method, by varying in each simulation, the number of holes to be sampled. Ten simulations were run; the later simulations were carried out for two fields only.

3.9.3 Modelling realized yield and present value

Damage and yield loss models in relation to different rodent population densities in maize fields can have an important role in the implementation of rodent control measures. In order to explore the effects of rodent damage on maize crop, a STELLA model for bioeconomics (Skonhoft *et al.* In press) was used with some modifications based on the relationship between rodent density and rodent damage at planting time. The description of Skonhoft *et al.* (In press) model is as outlined in section 3.9.4. A sigmoid function was used in the current study, whereas a hyperbola function was used in the model presented by Skonhoft *et al.* (In press). The sigmoid function was incorporated in the Skonhoft *et al.* (In press) model, and finally, the effective control strategies were determined. The following control strategies were used: (i) control for a given number of consecutive months, (ii) no control, (iii) control every month, (iv) control only for certain predetermined months (e.g. only in February or in February and November) and (v) control for symptomatic months (i.e. in March and July or both). The model therefore would establish whether rodent control measures should be or should not be taken and to find out the rewarding duration and the best strategies.

3.9.4 Modelling Rodent Outbreaks, Control Induced Mortality and Bioeconomics as Described by Skonhoft *et al.* (In press)

3.9.4.1 Modelling rodent outbreaks

Leirs *et al.* (1996,1997a) developed prediction models for outbreaks of *M. natalensis* in Tanzania and were further explored by Leirs (1999). The population dynamics of *M. natalensis* is governed by both density-dependent processes and density independent factors (Leirs, 1995). Rainfall is a density independent and time-dependent stochastic factor (Leirs, 1995). The model is based on studies using one hectare of land, while the agricultural area that need to be considered may be quite large. Dispersal of rodents is therefore ignored.

The model further describes only the female population due to the fact that the demographic parameter estimates are more reliable for females than for males. Also, the female population is instrumental in determining the population dynamics through reproduction, which is typically limited by the number of breeding females. An ecological model is a stage structured model (Getz & Haight, 1989) with four stages; where the vector $N_n = (N_{j0,n}, N_{j1,n}, N_{sa,n}, N_{a,n})$ describes the rodent population per ha at the beginning of month n. $N_{j0,n}$ is the number of juveniles in the nest, $N_{j1,n}$ is the number of juveniles which are weaned but not yet in the trappable population, $N_{sa,n}$ is the number of sub-adult (non-reproducing) individuals, and $N_{a,n}$ is the number of adult (reproducing) individuals. The total abundance at the beginning of month n is then given as $N_n = N_{j0,n} + N_{j1,n} + N_{sa,n} + N_{a,n}$.

The population dynamics is, in matrix form, represented by $\mathbf{N}_{n+1} = \mathbf{M}\mathbf{N}_n$, and where $\mathbf{M}$ is defined as (cf. Stenseth *et al.*, 2001):

$$(11)\quad \mathbf{M} = \begin{bmatrix} 0 & 0 & 0 & B(V_n, N^{(e)}_n) \\ s_{0n} & 0 & 0 & 0 \\ 0 & s_{0w} & (1-m_n)\cdot s_1(V_n, N^{(e)}_n)\cdot(1-\psi(V_n, N^{(e)}_n)) & 0 \\ 0 & 0 & (1-m_n)\cdot s_1(V_n, N^{(e)}_n)\cdot\psi(V_n, N^{(e)}_n) & (1-m_n)\cdot s_2(V_n, N^{(e)}_n) \end{bmatrix},$$

when B is the reproductive rate per adult female over one time step (being one month); s_{0n} is the monthly survival of juveniles still in the nest, and s_{0w} is the survival of juveniles during the first month after weaning, both assumed to be fixed irrespective of the environmental conditions; s_1 is the survival of sub-adults, s_2 is the survival of adults, and ψ is the maturation rate of sub-adults to adults (i.e., the probability that a subadult will mature to become a reproducing adult over the intervening month, given that it stays alive). The density relevant for defining the density-dependent structure of the demographic rates is given by $N^{(e)}_n = N_{sa,n} + N_{a,n}$ (juveniles are not yet recruited into the population and their number therefore does not affect the demographic rates). The parameter m_n, represents the reduction in natural survival, i.e., the death rate, due to pest control action during month n. Consequently, by definition, when $m_n > 0$ the population is being affected by the application of poison. The effect of the control is assumed to be the same for sub-adults and adults; hence, the same m_n. The control is assumed to have no effect on the juveniles as they are just born and still in the nest (or may be just out of the nest) and will not eat the poison. There are, therefore, no control effects operating through the survival rate of juveniles, s_0. Rainfall affects the demographic rates through the cumulative rainfall during the preceding three months $V_n = (P_{n-1} + P_{n-2} + P_{n-3})$ where P_{n-1} represents the amount of rainfall during the month n-1, etc. (Leirs *et al.* 1997a). The three-months time lag is used since rainfall has an indirect effect through vegetation (hence, the symbol V_n). The effects of density and precipitation are non-linear; below a certain rainfall or density threshold, the demographic parameters have one value, above the threshold, they have another value. The parameters of the ecological model are given in Appendix 6.

3.9.4.2 The control induced mortality

Stenseth *et al.* (2001) have explored how Leirs (1999) model (i.e. ecological model) behaves when a simple and fixed control-induced mortality is introduced. They show that not only the magnitude of m_n is important, but also over which period the control is applied; a permanently applied control may reduce the population considerably (and even drive the population to extinction), while there is little effect when control is applied at high densities only, even when there is large increase in mortality (Fig.8)

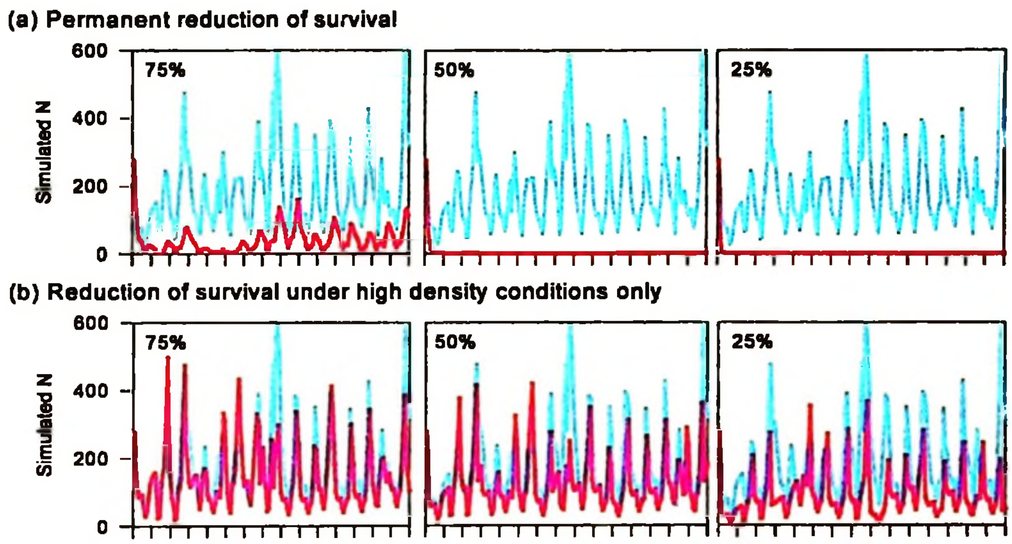


Figure 8: Simulation of lethal control of simple and fixed control-induced mortality

3.9.4.2.1 The control induced mortality; linking pest control measures to population dynamics

Analysis is restricted to control measures affecting survival, and where the effect on the control-induced reduction m_n of natural survival is assumed to result from the application of poison. Generally there is a two-stage effect on survival. Let X_n be the amount of control measures (i.e., some poison) applied per ha in month n. Its efficiency typically decreases with increasing precipitation during the month as the baits or the active ingredients degrade under humid conditions. In the present analysis, however, we can assume that precipitation has a negligible effect during the current month. In addition, we can make the reasonable assumption for the multimammate rat system in Tanzania that after one month no effect of the poison persists in the environment in a form being available to the rats (Buckle, 1994). Consequently, in what follows, the amount of effective control in month n coincides with the actual control measure in the same month (and given by X_n). In the numerical analysis, consistent with current practices in rural areas in Tanzania (Mwanjabe & Leirs, 1997), we can further assume that X_n is fixed either at zero or at some fixed non-zero level. The present control problem is therefore not aiming at optimising how much poison to use, of what type, and month to apply but which rodent density level can cause which magnitude of damage to maize crops and whether it can be controlled.

The demographic effect of pest control, the control or kill function (Carlson and Wetzstein, 1993), is generally represented by a function where the death rate increases with the management intensity; that is,

$m_n = m(X_n, N_n)$ ....[12]

The reduction in natural survival, being in the domain [0,1], is therefore given as $\partial m/\partial X_n \geq 0$ with $m(0,N_n) = 0$. $\partial m/\partial N_n \leq 0$ should also hold, but since the control measure operates through increased mortality, and not directly on the number of individuals killed, this effect can be quite complex. In the proceeding analysis, we have therefore chosen a pragmatic approach and neglected any influence through the size of the rodent population. For the given dosage X_n, we can assume that the combined effect of natural mortality and the rodenticide-induced mortality is constant and always 0.90. Hence, $(1-m_n)\bullet s_i(V_n,N^{(c)}_n)=0.1$ is fixed every month when rodenticides are applied, and $s_i(V_n,N^{(c)}_n)$ in other months (see the appendix 6).

3.9.4.3 Benefit and cost functions

Further-more, Skonhoft *et al.* (In press) explored more on the economics of rodent control. The model is as shown in Fig. 9. The economics of rodent control consists of two basic components; the cost of controlling the rodents and the benefits of doing so being realised through reduced crop damages. We can first formulate the yield function in the absence of rodents. However, the damage caused by the rats both during planting and harvesting is taken into account. Finally, the control cost function is introduced. The yield of maize depends on the quality of the agricultural land, labour input, fertiliser use, and rainfall (Ruthenberg, 1980). Empirical evidence from small-holder maize farming in Tanzania indicates some degree of substitution between fertiliser use and rainfall, while all other production factors are more or less fixed, or remain at a fixed proportion to the yield (Jensen *et al*,. 2003).

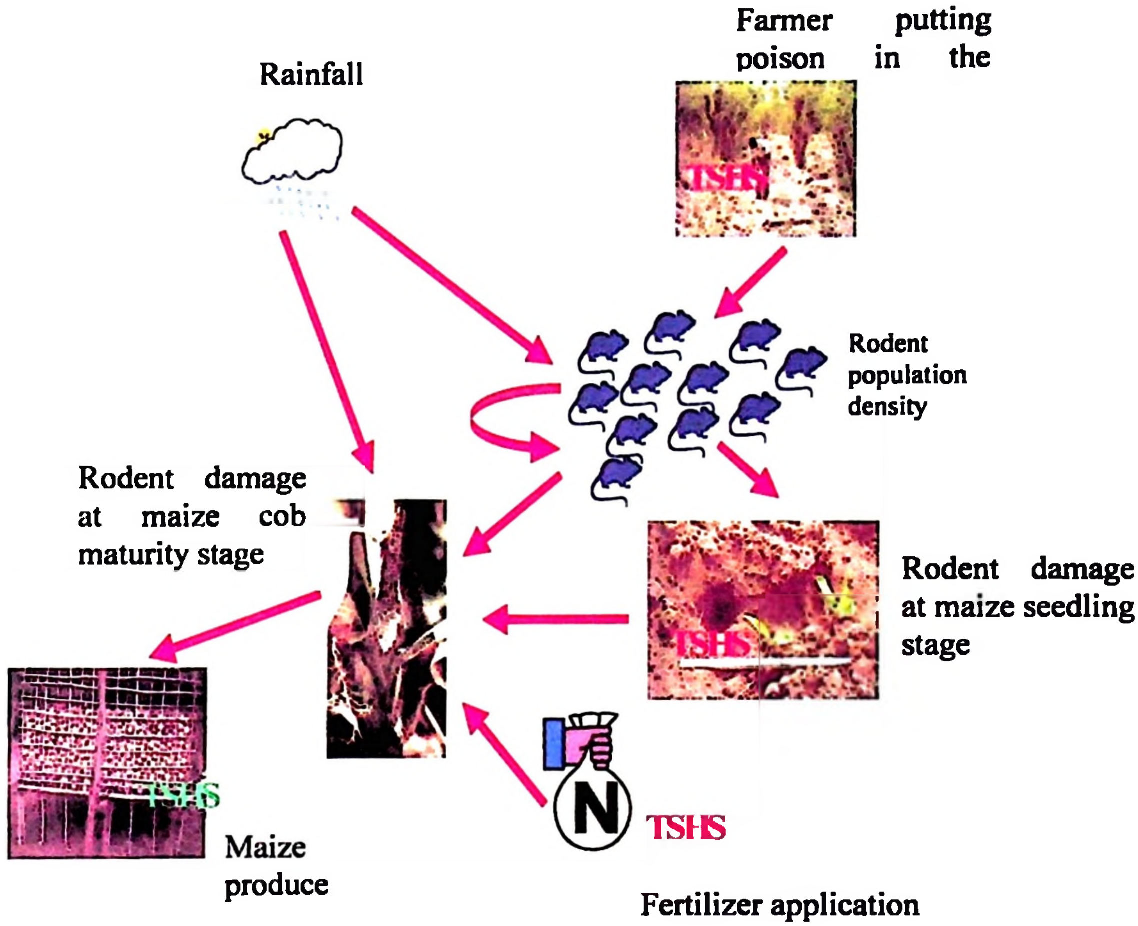


Figure 9: A skeleton of Skonhoft *et al.* (In press) account of the bio-economic interactions in agricultural rodent pest systems*.

**The rodent population is influenced by rainfall and intrinsic factors, which generate a particular density-dependent structure. Farmer's revenue derives from the sale of agricultural products minus the costs of production. The link between economics and rodents is both through the damage, which reduces the potential yield and through the cost of controlling the rodent pest, both of which enter the net income. The net income over a number of years, dependent on the planning horizon, is summed as the present value ($PV = FV * (1+i)^{-n}$, which is to optimized.*

Where: FV = future value, i = interest, n = time (years)

Assuming one crop per year and that fertiliser use and rainfall are the limiting production factors, the yield in kg per ha of agricultural land in absence of rats is

$Y_t = Y(F_t, A_t)$ ....[13]

where F_t is the amount of nitrogen fertiliser applied and A_t is the amount of rainfall accumulated throughout the maize growing season. The accumulated rainfall is assumed to be governed by the precipitation during the five months prior to harvesting (typically occurring before the August in Morogoro although this can hold true for a well distributed rainfall over the growing season). Consequently, we can have $A_1 = (P_3+\ldots+P_7)$ for the first year, and similarly for the remaining years. $Y(F_t, A_t)$ is generally increasing at lower rates in time in both A_t and F_t up to some threshold level i.e., $\partial Y/\partial F_t > 0$ and $\partial^2 Y/\partial^2 F_t \leq 0$, and $\partial Y/\partial A_t > 0$ and $\partial^2 Y/\partial^2 A_t \leq 0$. In addition, no rain means a small and negligible harvest, hence, $Y(F_t, 0) = 0$.

Rodent damage typically occurs immediately after planting and until the maize seedlings have reached the three-leaves stage (about 2-3 weeks after planting). When severe rodent damage on the seedlings becomes obvious (about ten days after planting), farmers may decide to replant. Nevertheless, the model was simplified by assuming that planting always (and only) occurs in March and that damage caused by rodents is not remedied by replanting. If rainfall in October to December (*Vuli*) is very abundant, which happens rarely, then planting is possible in that season as well. However, farmers generally do not trust *Vuli* rains since they are very unreliable. Hence, even though planting may be possible, they are skeptical that rainfall will not be sufficient during the rest of the growing season. Thus, planting in this season does happen only in some years, and even then, only few farmers decide to plant. Therefore, in this model we ignored this crop season. In general, damage caused by rodents has two components: one taking place during planting, expressed as a fraction of the yield, and another during harvesting, measured as absolute yield loss. Between seedling and ripening stages there is essentially no damage caused by the multimammate rat (Makundi *et al.*, 1999). Skonhoft et al. (In press) reported that the fraction of damaged maize seed planted in month n is directly related to the abundance of rats; that is,

$D^{p}_{n} = D^{p}(N_{n})$ ....[14]

with $\partial D^{p}/\partial N_{n} > 0$. The specific functional form $D^{p}_{n} = a+b\bullet Nn/(c+Nn)$ was used in in the numerical simulations; where, "a" represents the germination failure rate or damages not directly related to the rat population, "b" is the maximum damage level, and "c" is the rat density for which damage is b/2. The parameter values are shown in appendix 7.

However in this study, the sigmoid function for damaged maize seeds was used where the specific form is:

$$y = \frac{a}{1 + e^{\left(\frac{x - x0}{b}\right)}} \quad \text{..........[15]}$$

where "x" represents the germination failure rate or damages not directly related to the rat population, "a" is the maximum damage level, and "x0" is the rat density for which damage is b/2

Assuming no further rodent damage, the annual maize yield will then be $Y(F_t,A_t)\cdot(1-D^p_n)$. Again, there will be a further reduction during the harvesting period. At maturity stage of a crop, the damage measured in absolute loss (kg per ha), is also directly related to rodent abundance

$D^h_n = D^h(N_n)$ ....[16],

with $\partial D^h/\partial N_n > 0$ and $D^h(0) = 0$. The function is specific linear $D^h_n = d\cdot Nn$ where the value of "d" is based on information about the daily food consumption of rats. It is theoretically considered that small rodents on average, have a daily food intake of approximately 10% of their body weight (Petrusewicz & Macfadyen, 1970). *Mastomys natalensis* rats weigh on average 45 g during the pre-harvest period (Leirs, 1995). Rodent damage to ripening maize cobs starts approximately 1 month before harvest and assuming that rodents climbing the stalks damage about the same amount as what they actually eat, the parameter d was set to be d = 30 days x 4.5g/day x 2 = 270 g. The length of the maize growing season, τ, is 5 months from planting to harvesting for the composite maize variety, STAHA.

Consequently, the actual maize production in year t is

$NY_t = \max[0, Y(F_t, A_t) \cdot (1 - D^p(N_{n-\tau})) - D^h(N_n)]$ ....[17]

where the time-lag τ, the length of the maize growing season (typically five months), is introduced to scale the two types of damage occurring in different months. Gross agricultural profit per ha and year (i.e., the profit without accounting for the cost of rodent-control) is given as

$R_t = p \bullet NY_t - q \bullet F_t - K$ ....[18],

where p represents the 'net' market price of the crop; that is, the market price of the maize corrected for cost factors being in fixed proportions to the yield, q the fertiliser price and K the fixed costs. All costs and prices are assumed to be constant over time. In the following we can assume labour use, the basic production factor in addition to water and fertiliser, to be fixed per ha, and, hence, not related to the yield per ha. The opportunity cost of labour, if any, is therefore embedded in K. With these assumptions, p therefore basically reflects the price of maize.

The control cost at time n (i.e., month) is given as

$C_n = C(X_n)$ ....[19]

with $\partial C/X_n > 0$ and $C(0) = 0$. The specific functional form used in the simulations is assumed to be linear, $C_n = w \bullet X_n$, where the unit cost w essentially reflects the purchasing cost of the poison. However, the unit cost may contain the opportunity costs of labour linked to the spreading of the poison as well. If so, however, we are not explicitly considering any trade-off between labour uses in crop production and pest control. As already mentioned, consistent with recent practices in Tanzania, we can assume that X_n is fixed either at zero or at some non-zero level, and if applied, typically a treatment will be carried out with 2 kg of poisoned bait per ha. Hence, in the proceeding analysis C_n is fixed at some none-zero value per month whenever poison is applied, and zero otherwise.

Having defined the control and damage cost functions, the current net profit in year t reads

$\pi_t = p \bullet NY_t - q \bullet F_t - K - \sum C_n$..[20]

where the summation of the control cost is taken over the year (that is, n = 8 to 19 cover the year t = 1, etc). Equation 9 implies that the effect of discounting within the year is neglected. The current net profit function also neglects, if any, negative poison effects on crop production. Environmental costs caused by the poison are neither taken into account.

3.9.4.4 The management problem and the control strategies

While the crop profit without damage and control costs in one year is invariant of the current crop profit without damage and control costs in the previous year, this is obviously not so for the current net crop profit. Through damage and control costs, the net crop profit in one year is contingent upon the ecological state of the system in previous years. Hence, the net benefit in various years is linked together through the size of the rodent population. The management problem is therefore dynamic, and the problem is to find a control strategy X_n, being either zero or at some fixed non-zero level in a specified sequence of months over the year, reducing the survival rate m_n that balances the control costs and crop damages in a way that makes the present-value net profit per ha,

$$PV = \sum_{1}^{T+1} \frac{\pi_t}{(1+\delta)^t} \quad \text{.......[21]}$$

as large as possible over the planning horizon T years, while δ is the rate of discount. We can consider the management as a planning problem at the village level where the agricultural officer acts as the social planner. The planning horizon will then be expected to be relatively long in order to observed some variations while the rate of discount δ should reflect the social one. In the basic scenarios, we can use T =10 years and 7% rate of discount, δ =0.07.

In this model, an environmental situation is considered where both the crop yield and the rodent population growth are subject to large fluctuations since rainfall is largely stochastic. The ecology-economy interaction is also fairly complicated, basically due to the double and partly overlapping time scale. Moreover, in addition to X_n, the use of fertiliser F_t may also be considered as a control variable, making the problem even more complicated. Hence, rather than trying to formulate an optimising model within an optimal control (or programming) framework and finding one optimal control strategy among all possible that maximises present-value net profit, we can single out some reasonable main strategies and evaluate these outcomes in terms of present-value net profit.

The current rodent control practices consist mainly of symptomatic treatment when high rodent damage is noticed. In some cases, depending on the visible presence of many rats or issued outbreak warnings, farmers may choose to organise a prophylactic treatment at planting time. Such practices will be included in the analysis, but also analyse strategies where the control is applied for various consecutive months. All strategies include a fixed use of fertiliser, and F_t =40 kgN/ha was used in the basic simulations (i.e. recommended rate of application for Morogoro). However, the consequences of more fertiliser use, as well as no fertilising at all, was also included. The consequences of changing economic conditions were studied also. As baseline values p = 100 Tsh/kg maize, q =220 Tsh/kg fertiliser, w =6500 Tsh/kg poison, and K =10.000 Tsh/ha as the fixed cost were used.

The following control strategies X_n, were considered by Skonhoft *et al.* (In press), being either zero or at a fixed non-zero level, related to either the calendar or the state of the system, or both:

1) Control for a given number of consecutive months, including no control and control every month;

2) Control only for certain predetermined months (e.g., only every February or both February and March).

In addition to the above strategies with various conditions related to the state of the system (such as conditioning the application of poison or rodent density or precipitation).

Since rainfall patterns are a major component of the model's variability, simulations for Skonhoft *et al.* (In press) model were run with a large number of different rainfall series. Monthly rainfall values were used and were drawn from rainfall data obtained for that particular month in the period 1971-1997. For each month of the run, and independently from the values for the other months, a value was chosen randomly from the rainfall data for 27 years. For the control strategy, and set of model parameters, the model was run 100 times, each time with a different random value, resulting in 100 different rainfall series. The model simulations always started in December with an average number of animals comparable to what is observed in the field in that month (no juveniles, 133 sub-adult females and no adult females). In order to reduce the effect of initial conditions, each model was run for 248 months before pest control simulations and observations started; it then continued for a number of years, reflecting the given planning horizon, T. Accordingly, the evaluation of the profitability of each control strategy (i.e. no control and with control) is done by calculating the median present-value net profit (PV) of equation (19) for the 100 runs, together with the variability, given by the 95%-range values.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

This chapter is organised as follows: (i) actual damage, (ii) rodent damage pattern and distribution in maize fields, (iv) comparison of sampling techniques, (iv) rodent density, rodent damage and yield loss relationships, and (v) model simulations (for realized yield and net benefit for either no control or with control; for rodent densities predicted by population models).

The multimammate mouse *M. natalensis,* is the most destructive and the commonest rodent species found in Tanzania and Sub-Saharan Africa (Taylor, 1968). Quantification of damage and yield loss due to *M. natalensis* is necessary to establish the economic impact of this pest in agriculture. Knowledge of rodent damage patterns and damage distribution; sampling techniques will help to develop cost-effective control strategies. The relationships between rodent attack and yield losses are necessary for rodent management decisions to be made (Walker, 1990).

4.1 Actual Damage in Maize Fields

4.1.1 Actual Damage at Seedling Stage

Table 4 shows the actual percentage damage of maize at seedling stage in 15 fields during the 1999 and 2000 cropping seasons. The results show that in the first year (in two fields), the actual percentage damage was low compared with the second year (in thirteen fields). It can be seen that considerable differences in damage levels occur between years. These variations in rodent damage levels in different years were attributed to differences in rodent population density. In the second year, the rodent population was higher (almost three-fold) compared to the first year. It is known that the fraction of damaged maize seed planted in a certain month is directly related to the abundance of rodents (Mulungu *et al.*, 2003, Skonhoft *et al.*, In press). It was also noted that rodent damage differed between fields according to treatment. Fields with chicken mesh and covered by nets had higher rodent damage. This was probably due to free movements of rodents from outside the field and protection from predation (Vibe-Petersen *et al.*, submitted). Predation may affect rodents, possibly by influencing their foraging behaviour (Ives and Dobson, 1987). The overal actual rodent damage varied from 17.3 to 82.0% depending on treatment and year. The current estimates are higher than those reported by Makundi *et al.* (1991) and similar to those reported by Mwanjabe and Leirs (1997).

Table 4: Actual percentage damage of maize at seedling stage in 15 fields (i.e two fields in 1999 and thirteen fields in 2000 year)

Year	Name of the field	Actual %damage
1999	Field planted with maize and surrounded by fallowland (mosa13-19)	19.1
1999	Field planted with maize and surrounded by fallowland (CO1)	17.3
2000	Field planted with maize and surrounded by fallowland (mosa13-19)	58.1
2000	Field planted with maize and surrounded by fallowland (CO1)	50.7
2000	Open, with perches for attraction of predatory birds (PR2)	68.0
2000	Open, with perches for attraction of predatory birds (PR7)	59.5
2000	Field planted with maize and surrounded by fallowland (CO10)	70.5
2000	Field planted with maize and surrounded by fallowland (Mosa26-29)	63.3
2000	Field enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE3)	60.1
2000	Field enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE8)	63.7
2000	Field enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE5)	70.1
2000	Field enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE9)	62.3
2000	Field enclosed by chicken mesh and covered by nets (NO4)	75.1
2000	Field enclosed by chicken mesh and covered by nets (NO6)	82.0
2000	Experimental field, planted with maize located between other maize fields owned by farmers (Mono)	31.0

4.1.2 Actual damage at maturity stage

The actual proportion of cob damage was estimated in all fields but was very low or no damage was recorded in some fields in 2000 (Table 5). Considerable differences in cob damage occured between locations. At Mazimbu Campus Farm, the overal actual cob damage varied from 0 to 3.31%. This level is low compared to those reported by Everard (1966) in Nigeria (22.4%), Funmilayo (1976) in Nigeria (14.8) and Key (1990) in Kenya (5.4%) in maize.

Table 5: Actual proportion of cob maize damage in eight fields at maturity stage

Year	Type of field	Actual %cob damage
2000	Field planted with maize and surrounded by fallowland (mosa13-19)	0
2000	Field planted with maize and surrounded by fallowland (CO1)	0
2000	Field planted with maize and Open, with perches for attraction of predatory birds (PR2)	0
2000	Field planted with maize and Open, with perches for attraction of predatory birds (PR7)	0
2000	Field planted with maize and surrounded by fallowland (CO10)	0
2000	Field planted with maize and surrounded by fallowland (Mosa26-29)	0
2000	Field planted with maize and enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE3)	0
2000	Field planted with maize and enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE8)	0
2000	Field planted with maize and enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE5)	0
2000	Field planted with maize and enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE9)	0
2000	Field planted with maize and enclosed by chicken mesh and covered by nets (NO4)	0
2000	Field planted with maize and enclosed by chicken mesh and covered by nets (NO6)	0
2000	Experimental field, planted with maize located between other maize fields owned by farmers (Mono)	0
2000	Field planted with maize and surrounded by fallowland (DM1)	3.31
2000	Field planted with maize and surrounded by fallowland (DM2)	0.78
2000	Tractor disc ploughed field with maize and beans (DI5)	0.13
2000	Tractor disc ploughed field with maize and beans (DI6)	0.39
2000	Slash and burn field, planted with maize only (SM3)	0.16
2000	Slash and burn field, planted with maize only (SM4)	1.10
2000	Slash and burn field, planted with maize and beans (SI7)	0.29
2000	Slush and burn field, planted with maize and beans (SI8)	0.27

4.2 Rodent Damage Pattern and Distribution in Maize Fields

4.2.1 Rodent damage pattern and distribution at seedling stage

Rodent attack to maize starts at the time of sowing and later the seedlings are removed and consumed. Similar observations were made by various authors (Taylor, 1968; Mwanjabe, 1993; Mwanjabe and Sirima, 1993). Damage of maize occured again at maturity stage where longitudinal and circular cob damage occured. However, crop loss was much more serious at planting and seedling than at maturity stage. The pattern of damage in maize is similar to that observed in other cereals such as pearl millet and sorghum where rodents attacked the seeds after sowing and seedling more than at subsequent growth stages and maturity stage (Advani, 1982). However, the damage pattern for maize is different from that of wheat and rice where damage occurs throughout the growing season (Poché *et al.*, 1981). Hampson (1984) reported that in sugar cane, rodent damage occurs mainly at the internodes, and starts at the time of cane formation and persists to significant levels till harvest. Mwanjabe (1993) and Makundi *et al.* (1999) reported that rodent damage in maize crop at the early stages of the crop disrupts the planting program necessitating repeated planting.

The distribution of crop loss over a wide area is related to the pest distribution in both time and space (Kumar, 1984). However, populations of rodents do not only vary in relation to time, but also with spatial variation influenced by habitat type (Leirs, 1994). Rodent pests are, with a very few exceptions, favoured by high degree of habitat heterogeneity and discouraged by intensively cultivated mono-cultures (Myllymäki, 1987). The distribution of rodent damage in this study was either random (Fig. 10a) or regular (Fig. 10b), depending on the cropping patterns, but also showed variations between years (Table 6). A clustered distribution of rodent population was observed in the same fields (Massawe, 2003), but this was not the case for rodent damage. However, the damage in maize crop in the field cannot be determined only by the spatial distribution and density of rodent population, but also depends on the individual movements (Cheson, 1981). Mosaic fields support local populations and are connected by migrations where rodent damage could be regular as compared with monoculture fields.

Random damage distribution was observed in experimental fields planted with maize and located between other maize fields owned by farmers (Mono) surrounded by fallow land (Fig 10a; Table 6) not. These observations suggested that the individuals present in these fields after ploughing were either residents or passersby (no visitors from fallow) because the fallow land was far from the field investigated.

The timing of rodent damage and its distribution within the crop vary considerably with the rodent species, the surrounding environment and the age of the crop (Hampson, 1984). In rice, Buckle *et al.* (1985) and Schaefer (1975) reported that at low population density of *Rattus sp*, damage in rice fields was variable. Sometimes patches of severe damage were visible, while at other times, fields appeared to be free of damage but closer inspection revealed considerable damage which was evenly distributed over the entire field. When severe attack occurs, the most characteristic pattern is for the center of the field to be damaged, while border rows sustain little or no attack. This is probably a behavioural response, whereby the bunds, the most common focus for rodent activity, provide some degree of cover (Fall, 1977). A strong correlation between rodent damage in maize and the size of surrounding uncultivated land was reported in Kenya

(Key.1990). For sugar cane, Redhead and Saunders (1980) reported that the level of damage caused by *Rattus sordidus sordidus* and *Melomys littoralis* was related to the vegetation type adjacent to each field, with fields adjacent to overgrown, grassed wasteland suffering the most severe damage. For rice, Funmilayo and Akande (1977) reported that cane rats usually cut all the rice stems in an area systematically towards the center of the field. In Kenya, *Xerus erthropus* caused damage to maize seedlings and occasionally cobs along field edges (Key, 1990).

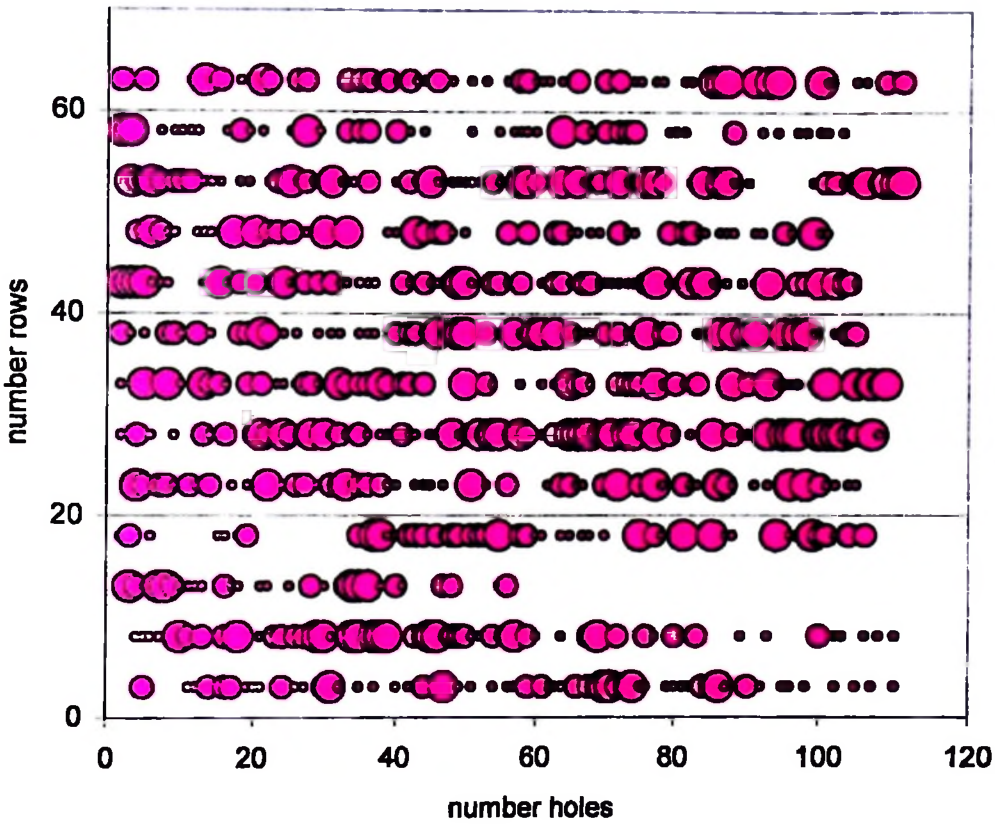


Figure 10a: Random rodent damage distribution (S^2/mean = 1.00) in maize fields (along the row [Big, medium and small sized bubbles indicate three, two and one seeds were removed, respectively. No bubble (empty) indicates no seeds were removed].

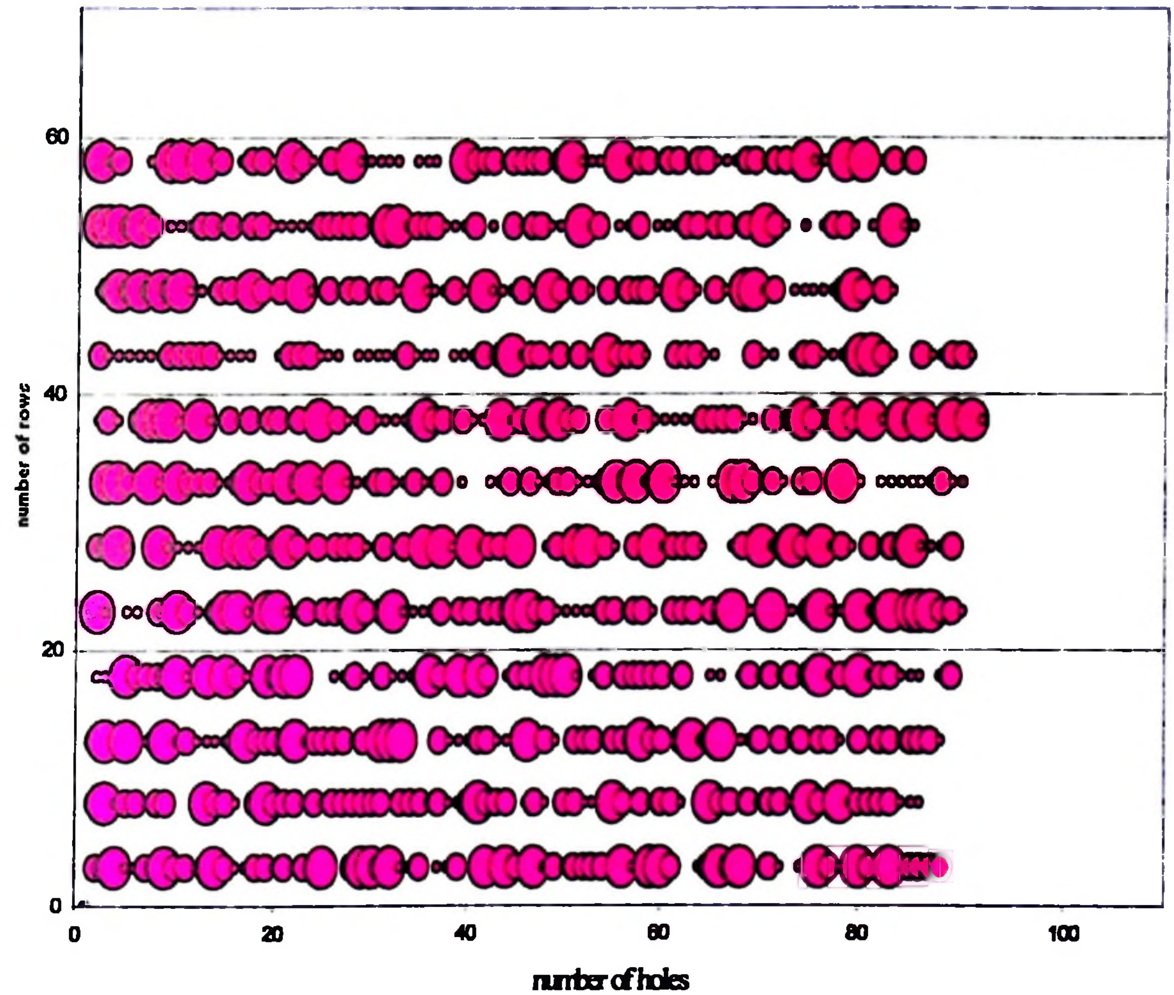


Figure 10b: Regular rodent damage distribution (S^2/mean = 0.39) in maize fields (along the row [Big, medium and small sized bubbles indicate three, two and one seeds were removed, respectively. No bubble (empty) indicates no seeds were removed].

Table 6: Variance:mean ratio and spatial distribution of rodent damage in thirteen maize fields.

Field name	Variance mean ratio (S^2/mean)	Damage distribution type
Field planted with maize and surrounded by fallowland (Mosa13-19)	0.56	Regular
Field planted with maize and surrounded by fallowland (CO1)	0.52	Regular
Field planted with maize and open, with perches for attraction of predatory birds (PR2)	0.43	Regular
Field planted with maize enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE3)	0.47	Regular
Field planted with maize enclosed by chicken mesh and covered by nets (NO4)	0.35	Regular
Field planted with maize enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE5)	0.42	Regular
Field planted with maize enclosed by chicken mesh and covered by nets (NO6)	0.22	Regular
Field planted with maize and open, with perches for attraction of predatory birds (PR7)	0.47	Regular
Experimental field, planted with maize located between other maize fields owned by farmers (Mono)	1.00	Random
Field planted with maize enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside; covered by a net to keep out predatory birds (NE8)	0.44	Regular
Field planted with maize enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside (CE9)	0.43	Regular
Field planted with maize and surrounded by fallowland (CO10)	0.39	Regular
Field planted with maize and surrounded by fallowland (CO1)	0.73	Random

Scale used for variance: mean ratio; <0.7 = regular, 0.7 - 1.3 = random, and >1.3 = cluster. Adopted from Kranz (1993).

4.2.2 Rodent damage pattern and distribution at maturity stage

Two types of cob damage were observed, viz. longitudinal, when missing kernels were along the length of the ear, and circular when missing kernels were in a ring form around the ear. Plates 7a-d show rodent and bird damage to maize cobs when the maize stems were standing upright or fallen. As a general observation, the few maize plants which were fallen were either attacked by rodents (Plate 7c) or guinea fowls (Plate 7d). Rodents consumed both milky and dry grains and this persisted until the crop was harvested.

At maturity stage of the maize crop more cob damage occurred at the periphery of the fields. However, it has been noticed that rodent damage to maize at maturity is often limited or negligible unless the maize plants have fallen to the ground due to attack mainly by termites. Therefore, termites damage to maize stalks at maturity stage is a prelude to considerable crop loss by rodents, which are unable to climb the stems. Rodent activity increased, especially when the surrounding cover was re-established. Similar observations were reported by Funmilayo and Akande (1977). Most of the damage was caused to ears on the disloged, or leaning plants; starting with the outer rows towards the centre of the fields.

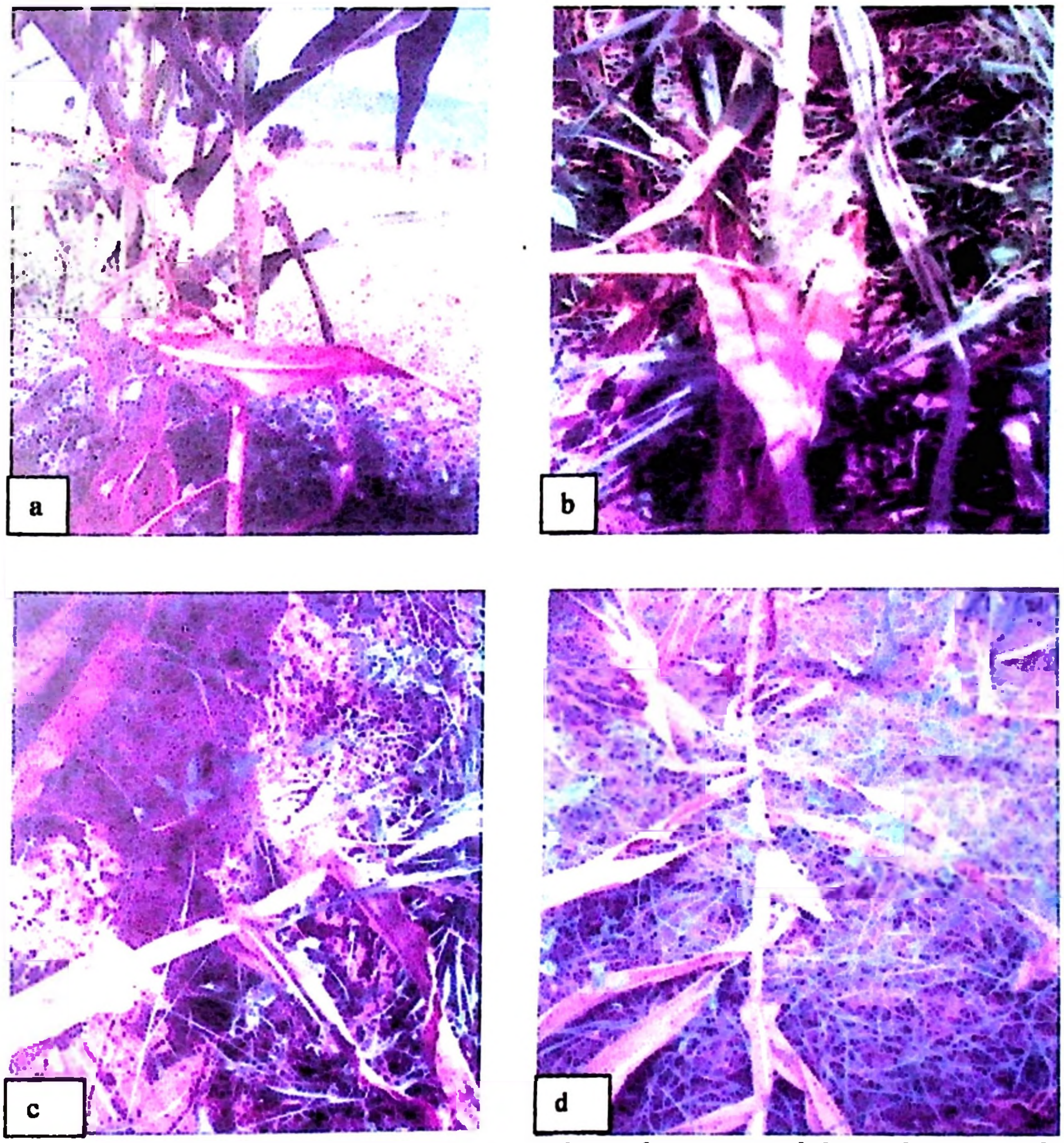


Plate 7: Rodents and bird damage to maize cobs: a = upright maize stem, in which mature cobs were damaged by rodents; b = upright maize stem, with cobs at milky stage damaged by rodents; c = fallen maize stem, with cobs damaged by rodents; and d = fallen maize stem, with cobs damaged by birds including guinea fowl.

Note: The damage occurred at the periphery of the fields.

4.3 Evaluation of Sampling Techniques

4.3.1 Comparison of sampling techniques

The average time spent per field for each sampling technique is shown in Table 7. Non-stratified systematic row sampling was the quickest method for damage estimation while non-stratified simple random required most time. In terms of complexity, non-stratified systematic row sampling technique was the simplest or least complex. Previous studies in maize and rice in Asia also indicated a preference for similar methods, mainly because of the technical complexities of random sampling (Hoque *et al.*, 1986; Rennison and Buckle, 1988; Bailey, 1994).

Table 7: Average time spent to collect samples per field of 70*70 m. for each sampling technique at seedling stage of maize crop.

Sampling technique	Time (h) spent per field (mean ± S.D.)	Sample size	Complexity
Non-stratified systematic row sampling	1.09 ± 0.05	15	Simple, little training required on how to count and select rows, no special equipment required
Stratified random square sampling	1.37 ± 0.19	15	Complex, requires training to identify and weigh strata, measure squares
Non-stratified Z-sampling	1.99 ± 0.08	15	Complex, requires measuring quadrats and distance between samples points
Non-stratified Simple random	3.34 ± 0.07	15	Very complex, requires understanding of the concept of randomness and/ or availability of random tables or something similar

For each sampling technique an estimate of accuracy or nearness to the actual damage was determined by using the coefficient of correlation (Edward, 1976). The higher the coefficient of correlation the closer the estimate was to the actual rodent damage.

The correlation analyses between estimated and actual damage during seedling stage and harvest period are summarized in Table 8. The results show that for all sampling techniques and crop growth stages, the observed r-values are different from zero ($p<0.001$). The non-stratified systematic row sampling technique had the highest correlation value compared to the other sampling techniques at seedling and maturity stages ($r = 0.99$; $p<0.001$, and $r = 0.98$; $p<0.001$, respectively). The non-stratified simple random technique had relatively lower correlation values ($r = 0.95$; $p<0.001$, $r = 0.88$; $P<0.001$) in all crop growth stages.

In theory, stratified sampling should give at least as good an estimate as non-stratified techniques (Conchran, 1977; Mead and Curnow, 1983) because the estimates are made on the damaged portion and its proportion to the total field. This was not the case in the current study where the spatial distribution of damage was either regular or random in the fields. Therefore, for these types of damage distribution in the field, it is more difficult to make a superficial assessment to allow division of the field into strata on which estimates of damage would be based. Based on the observed rodent damage distribution (i.e. regular or random) in this study, other non-stratified sampling techniques can be used and would give reliable and accurate damage estimates than stratification (Walker, 1987). Therefore, stratifying maize damage is only realistic if the fields being assessed show consistent differences in the various strata (Mead and Curnow, 1983).

Table 8: Relationship between actual and estimated damage at different growth stages of maize.

Crop stage	Sampling technique	Sample size (N)	Regression equation	Correlation coefficient (r)	Probability
Seedling stage	Non-stratified systematic row sampling	15	0.9569x+ 3.4356	0.99	p≤ 0.000
	Stratified random square sampling	15	1.1317x - 7.1491	0.97	p≤ 0.000
	Non-Stratified Z-sampling	15	1.0822x+ 1.9920	0.96	p≤ 0.000
	Non-stratified simple random	15	0.8512x+ 9.2012	0.95	p≤ 0.000
Maturity stage	Non-stratified systematic row sampling	8	1.5049x - 0.0046	0.98	p≤ 0.000
	Stratified random square sampling	8	1.7889x - 0.2691	0.95	p≤ 0.000
	Non-Stratified Z-sampling	8	1.6538x - 0.6518	0.95	p≤ 0.000
	Non-stratified simple random	8	3.5563x+ 0.1804	0.88	p≤ 0.000

The relationships between percentage damage and yield loss at planting and at maturity stage assessed by different techniques are shown in Table 9. The results show that non-stratified systematic row sampling technique had higher correlation values compared to the other sampling techniques at all crop growth stages. It further shows that the observed r-values were different from zero (P<0.001) except for stratified random square sampling techniques at maturity stage (not different from zero, P>0.05). This suggests that each stratum behaves like a separate entity in a field. Also, the results showed that non-stratified systematic row sampling gave high correlation determinations at crop maturity stage compared to the seedling stage. This indicates that maize damage at maturity is not compensated where as it occurs when damage occurs at planting stage probably due to better growth caused by reduced competition for resources (Judenko, 1973; Buckle, 1994).

Table 9: Relationship between damage and yield loss at different crop growth stages

Crop stage	Sampling technique	Sample size (n)	Regression equation	Correlation coefficient (r)	Probability
Seedling stage	Non-stratified systematic row sampling	15	6.6202x+ 565.82	0.75	P≤ 0.001
	Stratified random square sampling	15	7.013x + 553.02	0.73	P≤ 0.002
	Non-Stratified Z-sampling	15	5.954x + 569.28	0.75	P≤ 0.001
	Non stratified simple random	15	5.4955x+ 594.28	0.59	P≤ 0.022
Maturity stage	Non-stratified systematic row sampling	8	11.70x+ 172.77	0.95	P≤ 0.000
	Stratified random square sampling	8	31.358x+ 174.23	0.32	P= 0.440
	Non-Stratified Z-sampling	8	94.068x+ 23.094	0.95	P≤ 0.000
	Non-stratified simple random	8	49.301x+ 62.711	0.87	P≤ 0.005

4.3.2 Sampling intensity

All the tested sampling techniques (Table 8 & 9) gave reliable estimates of actual damage. However, non-stratified systematic row sampling was the simplest while non-stratified simple random was very complex. The non -stratified systematic row sampling and the non - stratified simple random techniques were further evaluated to establish the required sampling intensity.

The effect of sampling interval between rows for non-stratified systematic row sampling techniques is shown in Figs. 11 and 12. The computer simulations for different sampling intensities allowed quantitative description of the intuitively assumed relationship between sampling intensity and the accuracy of the estimate for both the non-stratified systematic row sampling and non-stratified simple random sampling techniques. The standardized variance (Fig.11) which is the ratio of variance of the estimated damage values with the mean actual damage for each sampling interval gives a measure of the proportional variance of the estimates. This shows an increase in estimates of variance when the interval between rows becomes larger. Taking the average values for all fields at each sampling interval (Fig. 12), a regression line was plotted and shows that the variation of an estimate stays below 10% of the actual damage when a sampling interval of less than 6 rows is used. For non-stratified systematic row sampling, the results show that the proportional variance of the estimates increased when the interval between rows became larger. This clearly shows that damage estimates become less reliable when the interval between rows increases (Conchran, 1977; Mead and Curnow, 1983). In some fields this effect was more dramatic than others, illustrating that damage is not equally distributed in all the fields.

The curve obtained (Fig. 12) can actually be used as a standard for future studies to decide what sampling row interval should be chosen for obtaining a desired accuracy, or what kind of accuracy can be expected for a given sampling row interval. The 5-rows interval used by Mwanjabe and Leirs (1997) seems to be a reasonable balance with a confidence level of 95%.

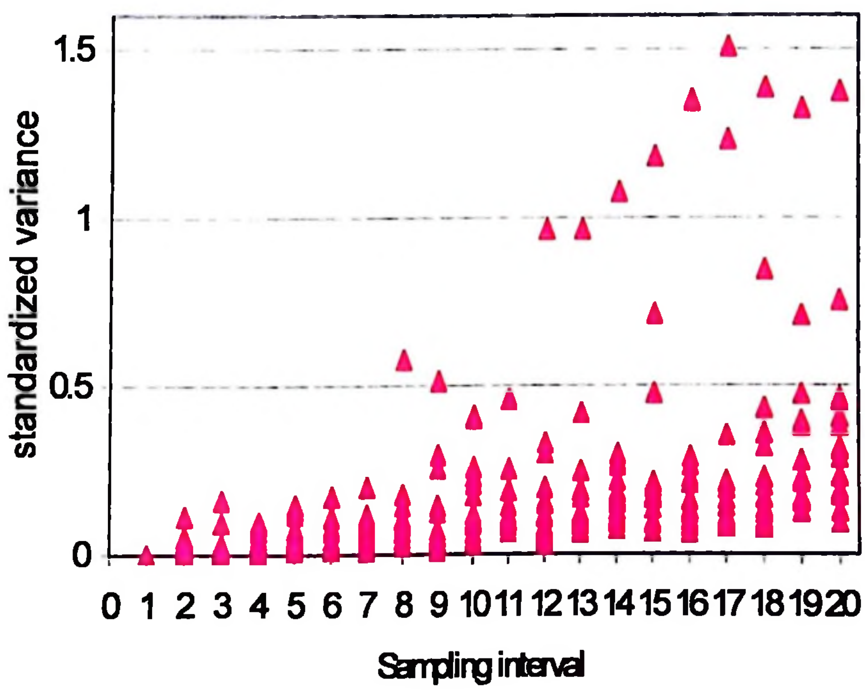


Figure 11: Relationship between sampling intensity and standardized variance of damage estimates using non-stratified systematic row sampling technique.

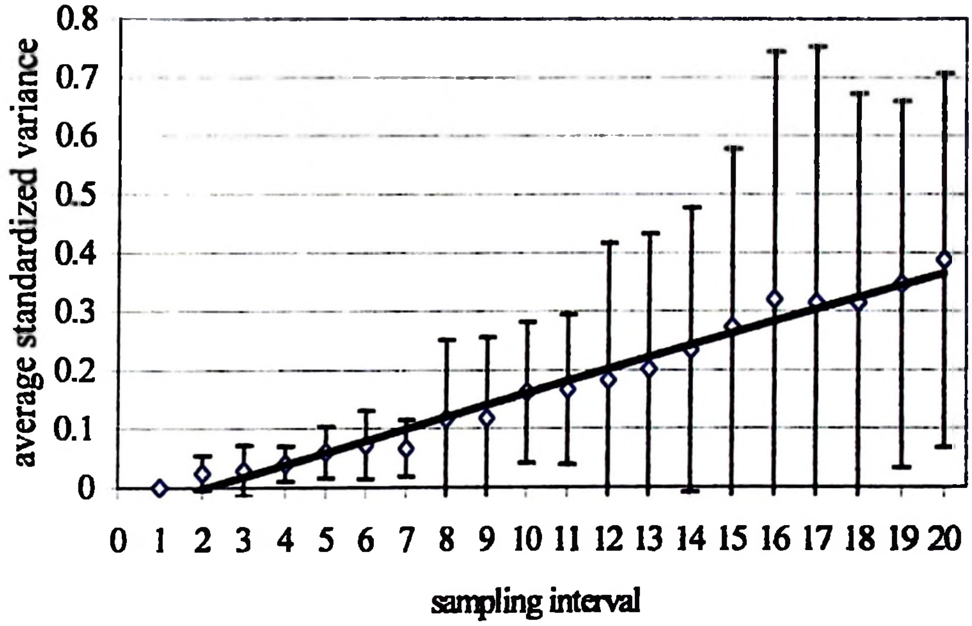
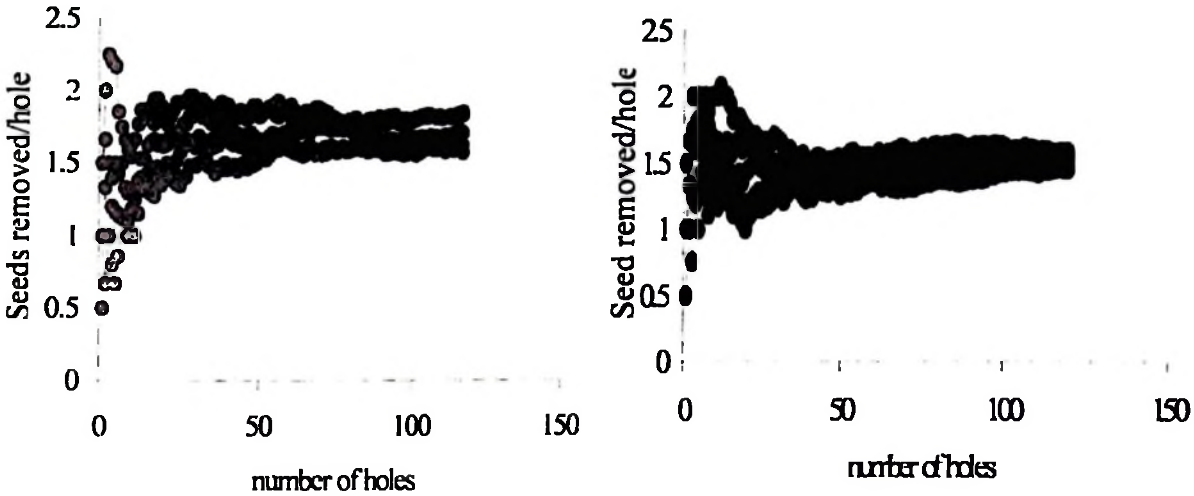


Figure 12: Relationship between sampling intensity and average standardized variance of damage estimates using the non stratified systematic row sampling techniques

With the non-stratified simple random sampling technique, estimated number of damaged seedlings per hole was very variable when only a few holes were sampled, but from a sample size of about 50 holes, the estimate stabilized (Fig. 13a & b). These results indicate clearly that when the number of holes sampled is more than 50, there is high reliability and therefore it is not advantageous to sample more than 50 holes. In a non-stratified simple random sampling, each hole in the field has an equal probality of becoming the actual sample and being selected without replacement. This is true regardless of the similarities or differences among them, as long as they are members of the same population (Bailey, 1994). In the current study therefore, 50 holes were the optimum sample size for non-stratified simple random sampling technique.



(a) (b)

Figure 13: Relationship between number of holes sampled in non-stratified random sampling and estimated number of seeds removed in two different fields.

4.4 Rodent Damage and Yield Losses in Maize

4.4.1 Relationship between rodent density and percentage rodent damage.

4.4.1.1 Relationship between rodent density and percentange rodent damage for both long and short rains

For decisions to be made about pest control, whether in maize or other crops in a cropping system, the relationship between population of rodents and damage must be known. This will allow decision making based on sound economic knowledge i.e. the benefits of reducing pest attack compared to the costs of control, and the relationship between yield and pest attack.

Mastomys natalensis causes damage to maize at three stages (viz. during planting time, seedling and the early stages of ear maturation to dry seeds). Often, rodent damage soon after planting (before germination takes place) is undetected (Funmilayo, 1976). However, at seedling and maturity stage, the damage is visible and distinct from that caused by other pests (Armstrong, 2002).

For the 1999 and 2001 long and short rains, there was a direct relationship between damage and rodent density (Fig. 14). For the 2000 long rains, there was also a direct relationship between damage and rodent density while for the short rains the relationship was an indirect one. These large variations in damage rates between seasons and years were expected because there were obvious variations in rodent population abundance and the amount of rainfall. During the short rains season in 1999, the percentage damage was higher than for the long rains season. This was attributed to a higher rodent density during the short rains season. Annual variations in rodent density was also observed. The population of rodents was highest during the second year than in the first and third years of the study and crop damage was also higher during the long rains season. Generally higher rodent damage occurred during the short rains season. This is probably due to: (1) little alternative food was available for rodents (2) germination was low and sporadic due to low rainfall, which suggests that germinating seeds and seedlings were available at intervals spreading over several days. (3) the population of rodents during the short rains was higher than during the long rains.

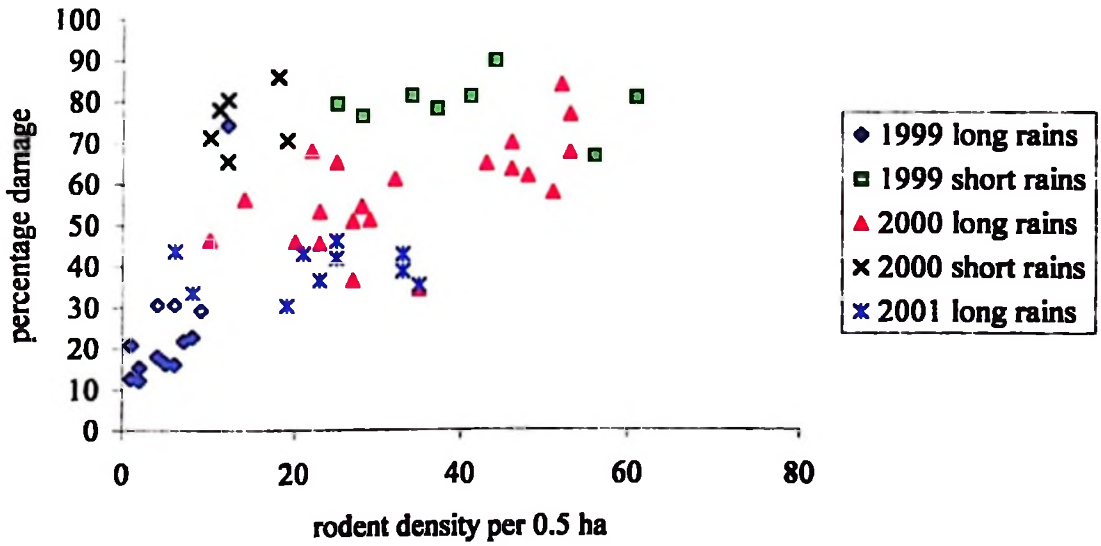


Figure 14: Relationship between rodent density and estimated percentage rodent damage.

Fourteen models were tested to find the appropriate one for the data in Fig. 14. Akaike's Information Criteria (AIC) were calculated for all 14 models and are shown (together with the coefficients and constants) in Table 10. The models are arranged in an ascending order starting from those with lowest AIC (Akaike, 1973). The results show that a sigmoid function ($r = 0.73$; $n = 58$; $p = 0.001$) with 4 parameters is the most appropriate model for these data. This however, does not differ from the second and third models in the series (Table 10).

Table 10: Relationship between rodent density and percentage damage at seedling stage using AIC criteria

No	Models and Coefficients	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 4 parameters: a = 38.54; b = 0.24; x0 = 9.36; y0 = 22.57, k = 4	321.72	0.00
(2)	Sigmoidal, Hill with 4 parameters: a = 38.52; b = 41.47; c = 9.34; y0 = 22.58, k = 4	321.73	0.01
(3)	Sigmoidal, Logistic with 4 parameters: a = 38.52; b = -41.53; x0 = 9.34; y0 = 22.58, k = 4	321.73	0.01
(4)	Sigmoidal Gompertz with 4 parameters: a = 38.00; b = 0.06; x0 = 9.37; y0 = 22.31, k = 4	321.99	0.27
(5)	Sigmoid with 5 parameters : a = 38.51; b = 0.27; c = 3.38; x0 = 8.86; y0 = 22.58, k = 5	323.74	2.02
(6)	6) Logarithm with 2 parameters II: a = 17.53; x0 = -1.02, k = 2	326.92	5.20
(7)	Hyperbola, single rectangular I with 3 parameters: a = 74.45; b = 7.36; y0 = 1.21, K = 3	328.38	6.66
(8)	Rational with 3 parameters II: a = 6.01; b = 0.59; c = 0.08, k = 3	328.38	6.66
(9)	Logarithm with 3 parameters: a = 16.00; x0 = -0.42; y0 = 5.49, k = 3	328.78	7.06
(10)	Logarithm, second order: a = 60.17; b = 0.12; y0 = 3.24, k = 3	328.87	7.15
(11)	Hyperbola, Modified hyperbola III: a = 84.44; b = 84.65; c = 0.23; d = 1.63, k = 4	330.37	8.65
(12)	Logarithm, third order: a = 4.86; b = 5.75; c = -0.87, k = 3	330.58	8.86
(13)	Linear regression with 2 parameters a = 0.81; y0 = 31.72, k = 2	335.72	14.00
(14)	Sigmoidal, Weibull with 5 parameters: a = 74.96; b = 0.00, c = 0.00, x0 = 9.00; y0 = 9.53, k = 5	336.87	15.15

List of Model equations used (the series is as indicated in Table 10), k = parameters

(1) Sigmoidal, sigmoid with k = 4

$$y = y_0 + \frac{a}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(2) Sigmoidal, Hill with k = 4

$$y = y0 + \frac{ax^b}{c^b + x^b}$$

(3) Sigmoidal, Logistic with k = 4

$$y = y0 + \frac{a}{1 + \left(\frac{x}{x0}\right)^{b}}$$

(4) Sigmoidal, Gompertz, k = 4

$$y = y0 + ae^{-e^{-\left(\frac{x-x0}{b}\right)}}$$

(5) Sigmoid with k = 5

$$y = y0 + \frac{a}{\left[1 + e^{-\left(\frac{x-x0}{b}\right)}\right]^{c}}$$

(6) Logarithm with k = 2

$$y = a\ln(x - x0)$$

(7) Hyperbola, single rectangular with k = 3

$$y = y0 + \frac{ax}{b + x}$$

(8) Rational with k = 3

$$y = \frac{1 + ax}{b + cx}$$

(9) Logarithm with k = 3

$$y = y0 + a\ln(x - x0)$$

(10) Logarithm, second order

$$y = y0 + a\ln x + b(\ln x)^{2}$$

(11) Hyperbola, Modified hyperbola III

$$y = a - \frac{b}{(1 + cx)^{\frac{1}{2}}}$$

(12) Logarithm, third order

$$y = y0 + a\ln x + b(\ln x)^{2} + c(\ln x)^{3}$$

(13) Linear regression with k = 2

$$y = y0 + ax$$

(14) Sigmoidal, Weibul with k = 5

$$y = y0 + a\left[1 - e^{-\left(\frac{x - x0 + b\ln 2^{\frac{1}{2}}}{b}\right)^{c}}\right]$$

The relationship between rodent population density, maize damage and yield loss is important in evaluating threshold population levels that will require control measures to be taken (Walker, 1990). The most parsimonious model (sigmoid with 4 parameters) is shown in the curve in Fig.15. Generally, the curve shows that rodent damage increases as rodent density increases, but it reaches a point where there is no further increase in crop damage despite an increase in rodent density. It is obvious from the curve that at low rodent density the level of damage is not influenced by change in numbers. However, above a certain level (>10 animals per 0.5 ha, or 20 animals per ha) a sharp increase in damage occurs. The increase in percentage damage is proportional to increasing rodent density. Damage reaches an asymptotic level where an increase of rodent density does not lead to an increase in crop damage because of reduced population of maize seedlings in the fields (Krebs, 1994; Smith, 1996; Smith and Smith, 2001; Krebs, 2001).

However, the curve shows great variation between observed and predicted rodent damage at intermediate rodent densities. This is presumably attributed to the rainfall factor because rainfall can affect both crop and rodent activity. Therefore, a correlation analysis between the total amount of rainfall at planting month and rodent damage was carried out. This aimed at reducing the variation between the two locations where the experiments were conducted. The results show a negative correlation ($r = -0.5598$) indicating that as rainfall increases during the planting month, rodent damage to maize decreases (Fig.16).

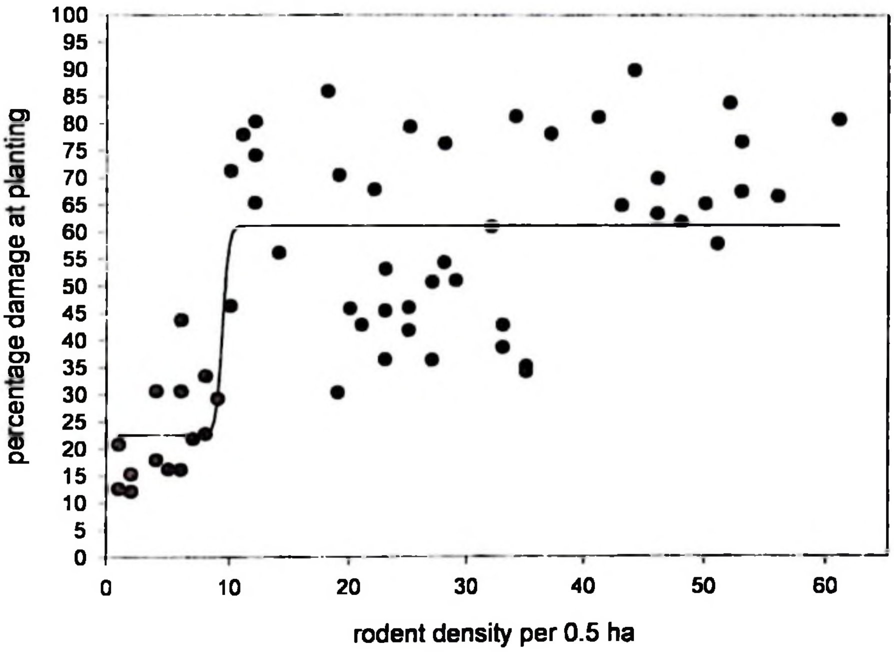


Figure 15: Relationship between population density of *Mastomys natalensis* per 0.5 ha and maize damage at sowing (A sigmoid curve best described these data and accounted for 54% of the variation).

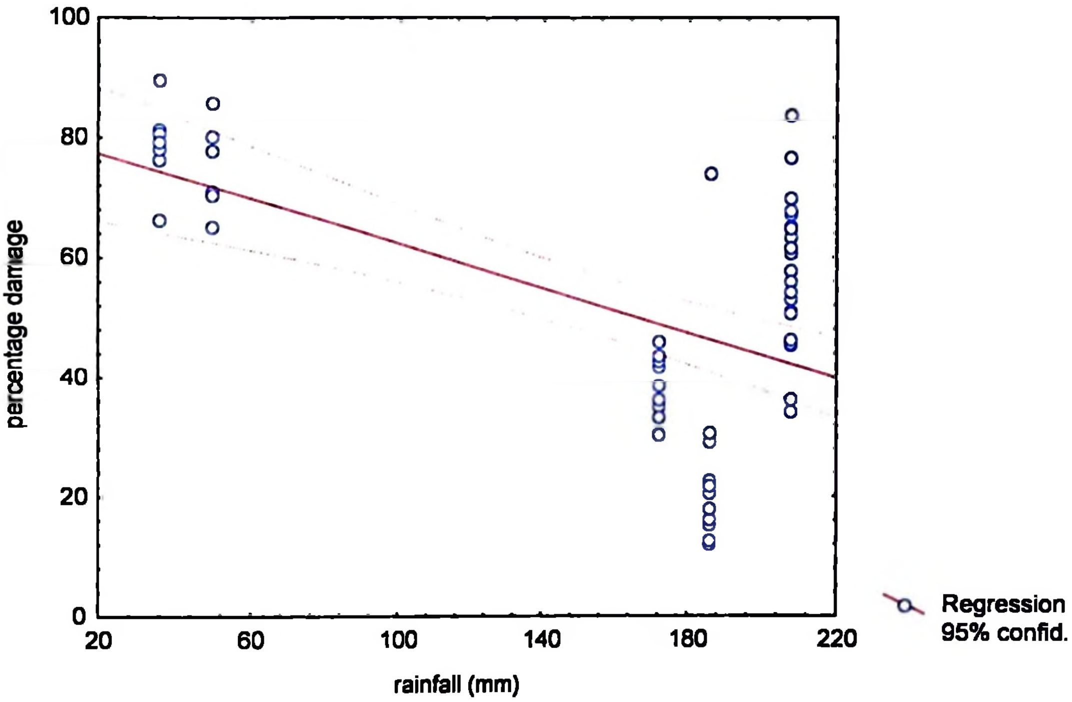


Figure 16: Correlation between total rainfall (mm) at planting and percentage rodent damage [Percentage damage = 81.097 - 0.1870*rainfall, r = -0.5598; significant at <0.05]

The rainfall factor was incorporated in the sigmoid curve, making a total of 5 parameters. The relationship between rodent density, total amount of rainfall during the planting month, and percentage rodent damage was conceptualized as a three-dimensional response. This response can be generalized as:

%damage = f(rodent density, amount of rainfall in a planting month)...................[20]

The results of the tested models are shown in Table 11 in ascending valuess of AIC. Models with a rainfall factor are better than those without in terms of the AIC values.

Table 11: Relationship between rodent density, percentage rodent damage and total rainfall in the planting month

No	Models and Coefficients	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the constant value. a =35.09; b = 0.36; x0 = 9.43; c = -0.13; y0 = 46.49	303.34	0.00
(2)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the numerator value. a = 58.90; b = 0.32; x0 = 9.38; c = -0.13; y0 = 22.44	304.12	0.78
(3)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the denominator value. a = 26027.54; b = 48.82; x0 = -327.09; c = 0.21; y0 = -25933.30	318.74	15.40

List of Model equations used (the series is as indicated in Table 11)

(1) Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the constant value

$$y = (y0 + c * rain) + \frac{a}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(2) Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the numerator value

$$y = y0 + \frac{a + (c * rain)}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(3) Sigmoidal, sigmoid with 5 parameters, including rainfall factor in the denominator value

$$y = y0 + \frac{a}{1 + e^{-\left(\frac{x - x0 + (c * rain)}{b}\right)}}$$

The model that is appropriate to the data is shown as a three dimensional plot of total rainfall in the planting month, percentage damage and rodent density in different fields (Fig.17). It is apparent that as rainfall increases, the percentage damage decrease regardless of rodent abundance.

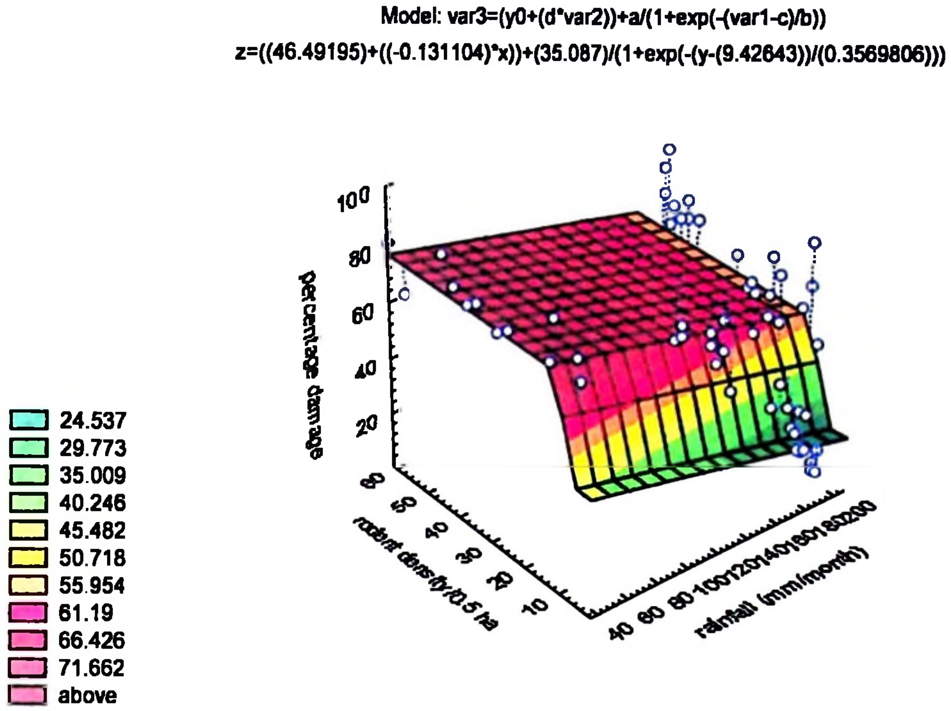


Figure 17: Three-dimensional surface response for the relationship between rodent density per 0.5 ha, percentage rodent damage and the amount of rainfall in the planting month.

Damage estimates were done 10 days after planting. Therefore, the amount of rainfall during the ten days after planting is more important than the total in a planting month. The amount of rainfall in the first ten days after planting was correlated with percentage damage. A negative correlation was obtained (Fig. 18), indicating that as rainfall increased during the first ten days after planting, damage by rodents decreased.

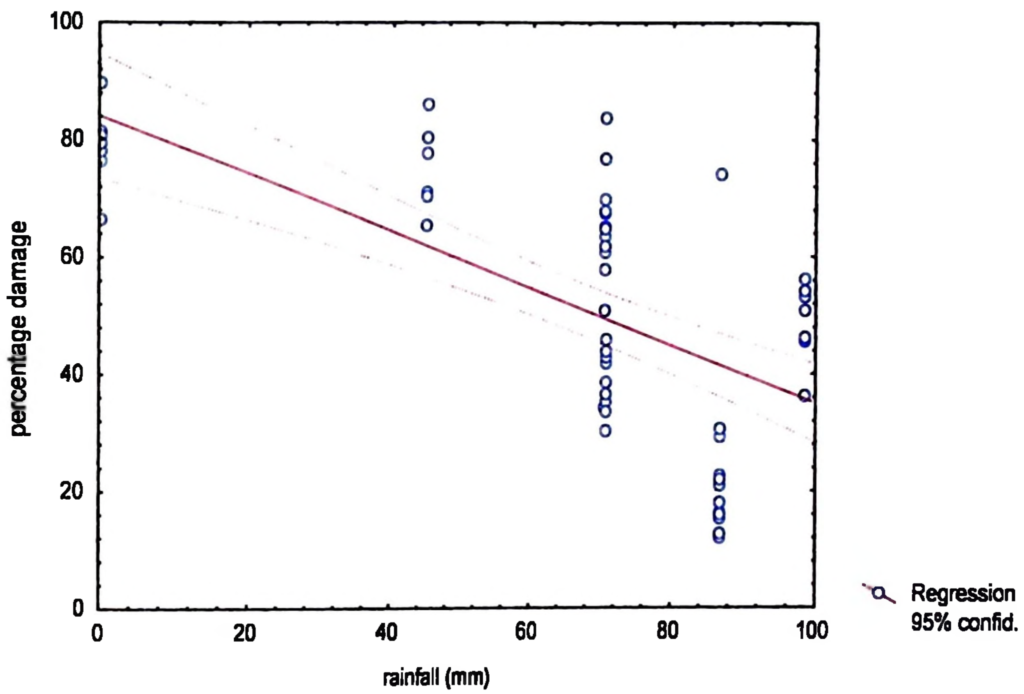


Figure 18: Correlation between total amount of rainfall (mm) during the first ten days after planting and percentage rodent damage to maize. [Percentage damage = 84.155 - 0.4915*rainfall, $r = 0.6657$; significant at $p<0.05$]

Similarly, three models were tested to compare the AIC with different positions of the fifth factor in the sigmoid curve with four parameters. The results of tested models are shown in Table 13 in ascending values of AIC. The model with a rainfall parameter as a constant and numerator factor improves the AIC compared to those without. These models are also the most appropriate for the data compared with models in which the rainfall parameter is added in the denominator. However, the best among the three models after incorporating the amount of rainfall during ten days after planting is when it is added as a constant compared to other models in which it was added either as a denominator or numerator (Table 12).

Table 12: Models for a three dimensional surface response between rodent density, percentage rodent damage and total rainfall during the first ten days after planting

No	Models and Coefficient	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a constant value. A = 29.95913; b = 0.05; x0 = 9.06; c = -0.34; y0 = 51.48	293.24	0.00
(2)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a numerator value. A = 57.89; b = 0.01; x0 = 9.71; c = -0.33; y0 = 23.07	295.76	2.52
(3)	Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a denominator value. A = 39.64; b = 120026; x0 = 3.43; c = 0.07; y0 = 2169974	322.20	28.96

List of Model equations used (the series is as indicated in Table 12)

(1) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a constant value

$$y = (y0 + c * rain) + \frac{a}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(2) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as the numerator value

$$y = y0 + \frac{a + (c * rain)}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(3) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as the denominator value

$$y = y0 + \frac{a}{1 + e^{-\left(\frac{x - x0 + (c * rain)}{b}\right)}}$$

Figure 19 shows a three dimension relationship between rodent density, damage and the amount of rainfall in the first ten days after planting. Damage of maize is low during high rainfall at both high and low rodent densities. This further indicates that rainfall is an important factor in determining the extent of damage to maize at planting.

Model: var3=(y0+(d*var2))+a/(1+exp(-(var1-c)/b))
z=((51.484)+((-0.3421965)*x))+(29.95913)/(1+exp(-(y-(9.055913))/(0.0505917)))

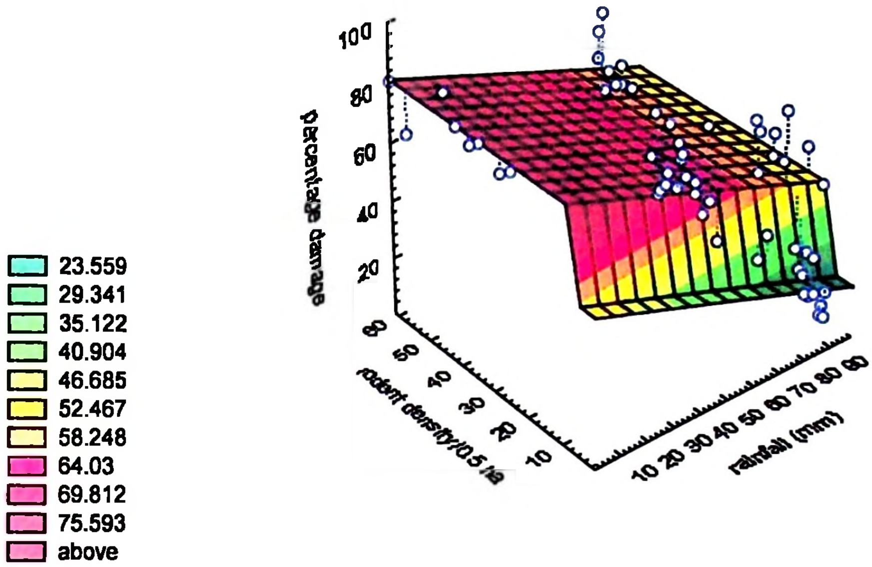


Figure 19: Three-dimensional surface response of the relationship between rodent density per 0.5 ha, percentage rodent damage, and amount of rainfall during the first ten days after planting.

Although the function (Sigmoid with 4 parameters) has the best AIC it is not very realistic. One of the problems of this model is that the intercept is far too high, i.e. when there are no rodents, the model predicts damage of arround 22%. Damage can also be more than 80% (own data) and yet the maximum in this model is 65%. The major cause of this discrepancy is the effect of rainfall. It seems that during the short rains, many maize seeds do not germinate due to lack of enough moisture in the soil. Therefore, failure in germination will be interpreted as rodent damage. In order to remove this discrepancy, the relationship between rodent density and rodent damage during the long rains cropping season was investigated.

4.4.1.2 Relationship between rodent density and rodent damage to maize during the long rains cropping season

The relationship between rodent density and rodent damage to maize for the long rain seasons in 1999, 2000 and 2001 was further investigated. The results show that rodent damage increased with increasing rodent density (Fig 20). For both 1999 and 2000, there was a direct relationship between maize damage and rodent density. This relationship was not so obvious in 2001. This was due to seasonal variations and rodent density differences. The variations in rodent density in different years was also observed by Vibe-Petersen (2003) and Massawe (2003) in the same fields.

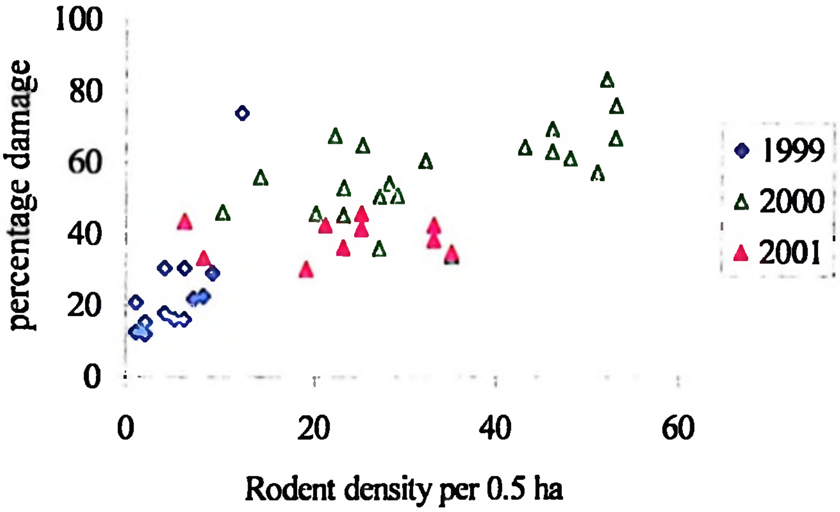


Figure 20: Relationship between rodent density per 0.5 ha and maize damage in different fields.

Twelve models were tested in order to obtain the most appropriate for the data in Fig. 20. AIC were calculated for all 12 models and are shown in Table 13 together with the coefficients and constants. The models are arranged in an ascending order starting from the lowest AIC. The results show that a sigmoid function ($r = 0.74$; $n = 44$; $p \leq 0.001$) with 3 parameters is the most appropriate model for these data.

Table 13: Relationship between rodent density and maize damage at seedling stage using AIC criteria

No	Models and Coefficients	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 3 parameters: a = 69.70; x0 = 15.83; b = 11.69	238.84	0.00
(2)	Linear regression with 2 parameters: y0 = 22.22; a = 0.93	240.32	1.48
(3)	Logarithm first order: y0 = 5.36; a = 13.94	240.59	1.75
(4)	Hyperbola with 2 parameters: a = 72.85; b = 10.51	240.68	1.84
(5)	Sigmoidal. Logistic with 3 parameters: a = 174.69; x0 = 96.25; b = 0.70	241.89	3.05
(6)	Sigmoidal. Sigmoid with 4 parameters: y0 = -164.96; a = 276.30; x0 = -24.32; b = 39.95	241.93	3.09
(7)	Exponential rise to maximum with 3 parameters: y0 = 94786; a = -94786342; b = 102335100	242.63	3.79
(8)	Sigmoidal. Logistic with 4 parameters: y0 = 10.83; a = 128.74; x0 = 56.30; b = -1.04	243.38	4.54
(9)	Hyperbola with 3 parameters: y0 = 12.92; a = 79.82; b = 29.42	244.32	5.48
(10)	Logarithm second order: y0 = 14.32; a = 2.61; b = 2.42	244.90	6.06
(11)	Power; a=1.05; b= 12.63; c = 0.41	244.96	6.12
(12)	Logarithm third order: y0 = 13.99; a = 3.72; b = 1.81; c = 0.13	247.33	8.49

List of Model equations used (the series is as indicated in Table 13), k = parameters

(1) Sigmoidal, sigmoid with k = 3

$$y = \frac{a}{1+e^{-\left(\frac{x-x0}{b}\right)}}$$

(2) Linear regression with k = 2

$$y = y0 + ax$$

(3) Logarithm, 1st order

$$y = y0 + a\ln x$$

(4) Hyperbola with k = 2

$$y = \frac{ax}{b+x}$$

(5) Sigmoidal, Logistic, with k = 3

$$y = \frac{a}{1+\left(\frac{x}{x0}\right)^{b}}$$

(6) Sigmoidal, sigmoid with k = 4

$$y = y0 + \frac{a}{1+e^{-\left(\frac{x-x0}{b}\right)}}$$

(7) Exponential rise to max. with k = 3

$$y = y0 + ae^{\left(\frac{-x}{b}\right)}$$

(8) Sigmoidal, Logistic with k = 4

$$y = y0 + \frac{a}{1+\left(\frac{x}{x0}\right)^{b}}$$

(9) Hyperbola, Single Rectangular wit k = 3

$$y = y0 + \frac{ax}{b+x}$$

(10) Logarithm, 2rd order

$$y = y0 + a\ln x + b(\ln x)^2$$

(11) Power

$$y = abx^{c}$$

(12) Logarithm, 3rd order

$$y = y0 + a\ln x + b(\ln x)^2 + c(\ln x)^3$$

Using the best fitting (sigmoid with 3 parameters) model, a curve was plotted for this relationship and shows that rodent damage to maize increases as rodent density increases, but reaches a point (> 60%) where there is no further increase in crop damage despite increasing rodent density (Fig. 21).

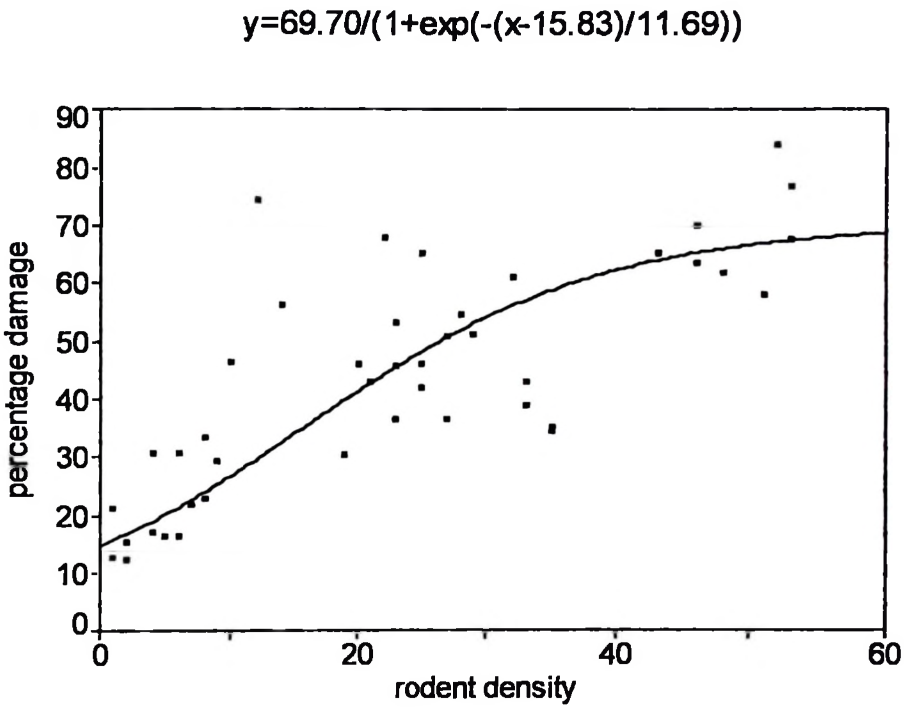


Figure 21: Relationship between density of *Mastomys natalensis* (per 0.5 ha) and maize damage at sowing. [A sigmoid curve best describes these data and accounted for 55% of the variation].

The relationship between rodent density and maize damage was best described by a sigmoidal, sigmoid function with three parameters (Fig.21). The model shows that 55% of the variation in rodent damage is explained for by the density of rodents at the seedling stage. It has an intercept of about 14%, which corresponds to a realistic germination failure rate. The other models gave intercepts greater than 14%. It is obvious from the curve (for an appropriate model) that even at low rodent density, there is considerable damage but the damage increases with increasing rodent density. However, damage reaches an asymptotic level at high rodent density (>40 animals per 0.5 ha field, equivalent to 80 animals per ha). In terms of rodent management therefore, the results suggest that unless the rodent population in the field is reduced to below 20 animals/ha there is a likelihood of economic damage to the maize crop.

The reason for an asymptotic relationship at high rodent density is probably because maize seeds in the field become scarce and, therefore, rodents probably switch to alternative and more abundant food sources such as insects and weed seeds. Murdoch and Oaten (1975) as cited by Krebs (2001) stated that this switching to alternative food resources is caused by two kinds of behaviour. These are: changing preference toward the more abundant food resource; ignoring the rare food resources and therefore concentrating search effort on more rewarding areas. This behaviour could thus benefit rodents by allowing them to maintain a stable population size (Krebs, 1994; 2001) particularly when maize seeds and seedlings become unavailable at high rodent population density. Similar observations were reported by Arneson (2001) in insects. It has been reported that rats in enclosures can cause less damage to crops due to intraspecific competition (Choate, 1972). However, in the current study the rodents were not enclosed and therefore it could be assumed that intraspecific competition was minimal.

At high rodent density, the actual damage deviated much from the predicted. These deviations at high rodent density may be due the effect of environmental factors. One of the factors which can influence both rodent activity and crop performance is rainfall. Therefore, the total amount of rainfall at planting and in the first ten days after planting was correlated with rodent damage (Figs. 22 & 23). Although a negative correlation between these variables was obtained, damage was high at low rainfall. The general trend shows that at low rainfall the damage is high. This occurs possibly because germination is low and sporadic and hence, germinating seeds and seedlings will be available at intervals spreading over several days (Key, 1990).

Rodent damage not only depends on the number of rodents in the field, but also on the duration of germination, which is dependent on rainfall distribution (Walker, 1987). However, at high amount of rainfall rodent damage increased (Fig. 22 & 23) indicating that, the soil becomes waterlogged. Waterlogging makes maize seeds to lack oxygen, hence increases germination failure rate, which will be interpreted as rodent damage. The importance of rainfall to rodent damage was also reported by Pomeroy and Gichuki (1981) and Key (1990) in maize and Poché *et al.* (1982); Posamentier and Alam (1980) and Fiedler *et al.* (1981) on rodent damage to wheat.

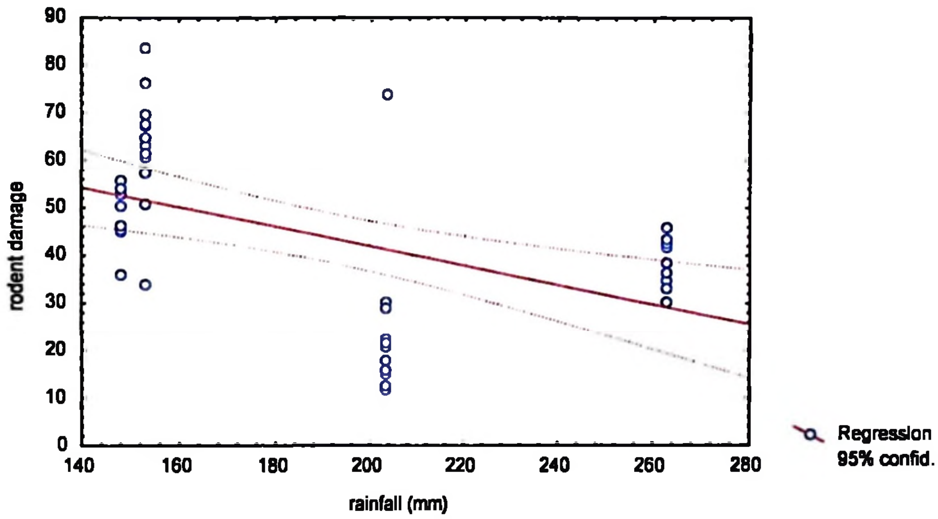


Figure 22: Correlation between total rainfall (mm) at planting and percentage rodent damage during the long rains cropping season. [Rodent damage = 82.865 - 0.2043*rainfall, r = -0.4824].

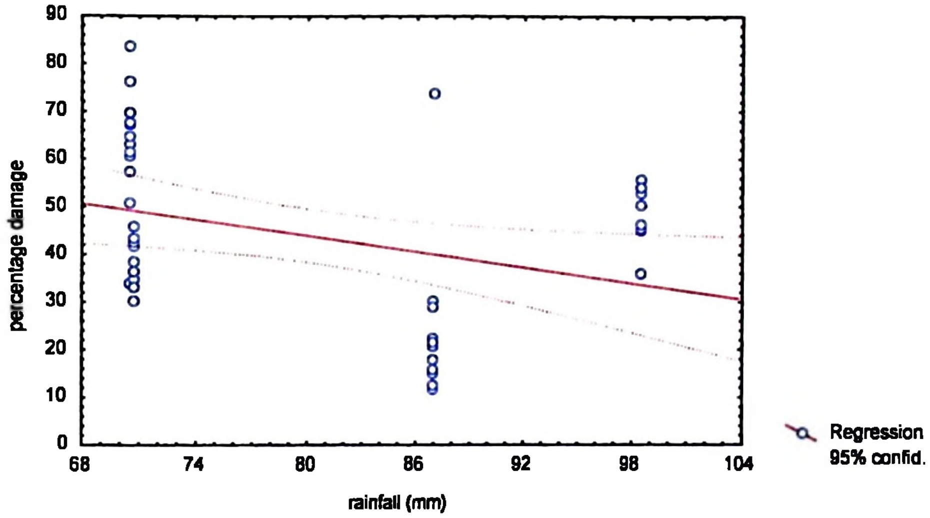


Figure 23: Correlation between total amount of rainfall (mm) during the first ten days after planting in the long rains cropping season and percentage maize damage. [Percentage damage = 88.581 - 0.5577*rainfall; r = -0.3280].

The rainfall factor (the amount of rainfall in a planting month) was incorporated in the sigmoid curve, making a total of 4 parameters. The relationship between rodent density, total amount of rainfall during the planting month, and percentage rodent damage similarly was conceptualized as a three-dimensional response. This response surface can be generalized as:

%damage = f(rodent density, amount of rainfall in a planting month)...................[21]

The results of the tested models are shown in Table 14 in ascending valuess of AIC. The model with an added rainfall paramcter as a numerator ($r = 0.85$; $n = 44$; $p \leq 0.001$) improves the AIC more compared to when the rainfall paramcter is added as a denominator or as a constant. This model was better than without the rainfall factor. Therefore, it could be interpreted that when rainfall is high, the resulting rodent damage is low irrespective of the rodent density.

Table 14: Relationship between rodent density, percentage maize damage and total rainfall in the planting month during the long rains cropping season

No	Models and Coefficients	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 4 parameters, including rainfall factor in the numerator value. a =80.98; x0 = -0.96; b = 0.01; d = -0.16	232.28	0.00
(2)	Sigmoidal, sigmoid with 4 parameters, including rainfall factor in the denominator value. a = 52.15; x0 = -10.55; b = 0.15; d = -0.03	241.67	9.39
(3)	Sigmoidal, sigmoid with 4 parameters, including rainfall factor as a constant value. a = 82.87; x0 = 26.10; b = -1.80; d = -0.20	254.56	22.28

List of Model equations used (the series is as indicated in Table 14)

(1) Sigmoidal, sigmoid with 4 parameters, including rainfall factor in the numerator value

$$y = \frac{a + (d * rainfall)}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(2) Sigmoidal, sigmoid with 4 parameters, including rainfall factor in the denominator value

$$y = \frac{a}{1 + e^{-\left(\frac{x - x0 + d * rainfall}{b}\right)}}$$

(3) Sigmoidal, sigmoid with 4 parameters, including rainfall factor as a constant factor value

$$y = (d * rainfall) + \frac{a}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

The most appropriate best model is further shown in Fig.24 as a three dimensional plot of total rainfall in the planting month, percentage damage, and rodent density in different fields. The results further indicate that at low rainfall the rodent damage is high.

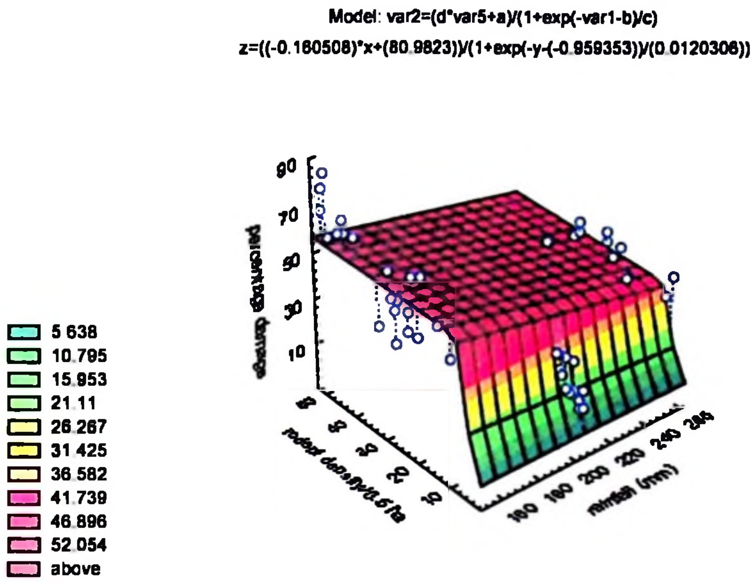


Figure 24: Three-dimensional surface response for the relationship between rodent density per 0.5 ha, percentage rodent damage, and the amount of rainfall in the planting month during the long rains cropping seasons.

Three models were tested to compare the AIC with different positions of the fourth factor in the sigmoid curve (with three parameters) with rainfall during the 10 days after planting. The results of the tested models are shown in Table 16 in ascending values of AIC. Both models do not improve the AIC compared to the model without rain factor (i.e. when rainfall parameter is not added in the function). The sigmoid function ($r = 0.81$; $n = 44$; $p \leq 0.001$) with four parameters in which rainfall is included as a denominator is appropriate for the data than the other models (Table 15).

Table 15: Models for a three dimensional surface response between rodent density, percentage maize damage, and total rainfall in the first ten days after planting during the long rains season

No	Models and Coefficient	AIC	ΔAIC
(1)	Sigmoidal, sigmoid with 4 parameters, including rainfall factor in the denominator value. a = 52.15; x0 = 5.43; b = 0.12; d = 0.11	241.65	0.00
(2)	Sigmoidal. sigmoid with 4 parameters. including rainfall factor in the numerator value. a = 89.33; x0 = 24.30; b =-3.50; d = -0.57	261.12	19.47
(3)	Sigmoidal, sigmoid with 4 parameters, including rainfall factor as a constant value. a = 89.33; x0 = 25.10; b = -12.02; d = -0.57	261.12	19.47

List of model equations used (the series is as indicated in Table 15)

(1) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a denominator value

$$y = \frac{a}{1 + e^{-\left(\frac{x - x0 + d * rainfall}{b}\right)}}$$

(2) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a numerator value

$$y = \frac{a + (d * rainfall)}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

(3) Sigmoidal, sigmoid with 5 parameters, including rainfall factor as a denominator value

$$y = (d * rainfall) + \frac{a}{1 + e^{-\left(\frac{x - x0}{b}\right)}}$$

Contrary to what was observed in Fig. 24, the three dimension relationship between rodent density, damage and the amount of rainfall in the first ten days after planting shows that regardless of the amount of rainfall, rodent damage increased with increasing rodent density during the ten days after planting (Fig 25). This indicates that the amount of rainfall in ten days after planting during the long rains cropping season is not a major factor affecting maize damage. The reason could be that: (1) the amount of rainfall for the ten days after planting is enough for the maize seeds to germinate uniformly, thus reducing the duration of risk of attack (Key, 1990). (2) it is known that rodents mainly use odour of planted seeds (during imbibition time) to locate them (Johnson and Jorgensen, 1981). Therefore, during the long rains cropping season, all maize seeds have an equal chance to be predated by rodents in the first ten days after planting.

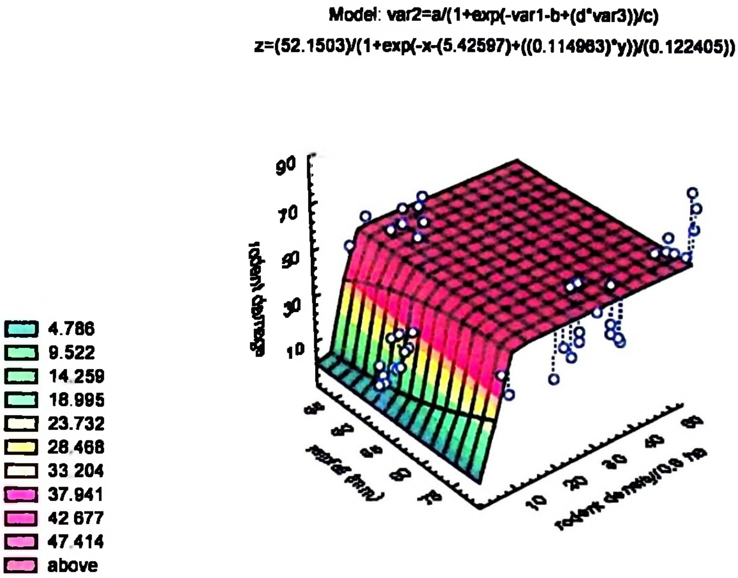


Figure 25: Three-dimensional surface response of the relationship between rodent density per 0.5 ha, percentage maize damage and amount of rainfall during the first ten days after planting in the long rains cropping season.

4.4.2 Relationship between rodent densities, damage and yield loss at planting.

4.4.2.1 Calculation of yield loss:

The relationship between yield loss at harvest due to maize damage at planting and rodent density was investigated. The average yield of an undamaged maize cob was calculated in a plant surrounded by other undamaged plants (in order to avoid the compensation effect of plants whose neighbours were predated). The expected yield per field in the absence of rodents was calculated as 14,700 (the total number of planted seeds per field) times the average yield of a cob. Each maize plant of the variety Staha produces one cob. Actual yield was measured and yield loss was calculated as the difference between the two (Table 17). The average yield of an undamaged cob in 1999 was 0.09 kg (90 g, n = 46, st dev = 0.098). However, for other years, expected yield was calculated from the relationship between yield and cumulative rainfall in the five months of maize growing period (Fig.26). The maize yield is directly related to the amount of rainfall in the growing season (Jensen *et al.*, 2003). Although such a curve is oversimplifying the relation between rainfall and maize yield, it does provide us with a rough estimate of the expected yield.

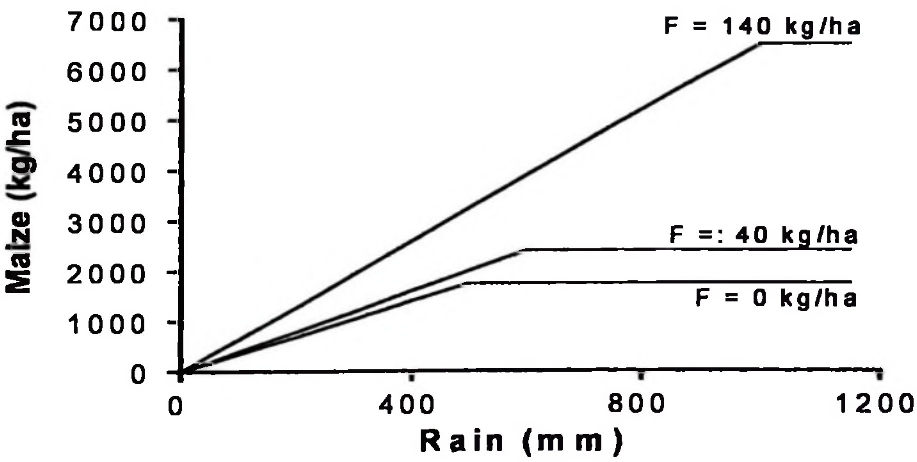


Figure 26: Maize yield functions, dependent on the amount of nitrogen fertilizer applied and rainfall during the growing season (Adopted from Jensen *et al*,. 2003)

The curve in Fig. 26 was obtained in a study carried out in Iringa region Tanzania. In experimental fields in this study, 40 kg N/ha of fertilizer was applied, and the predicted value according to the curves for 1999 with a total rainfall of 5485.8 mm during the growing season, would have been 1209 kg. The estimated expected yield was 1323 kg. The value for expected yield in experimental fields was assumed to follow a similar pattern as shown as Fig. 26, but with a slightly steeper slope. The expected yields in experimental fields in the absence of rodents are given in Table 16.

The relationships between these yield values and rodent population density were compared. Elaborated model selection was not used, but verification of whether there was a simple linear relation between rodent density or damage and (proportional) yield loss was carried out.

Table 16: Expected yield[1], actual yield and yield loss of maize due to rodent damage at planting and maturity stage.

Year	Field	Cumulated Rainfall	Expected yield (kg)	Actual yield (kg)	Yield loss (kg)	Yield loss at planting	%yield loss at planting	Yield loss at maturity	% yield loss at maturity
1999	Mosa26	545.8	1323	563.1	759.9	759.9	57.4	0	0
1999	Mosa13	545.8	1323	502.4	820.6	820.6	62.0	0	0
1999	Mono	545.8	1323	270.5	1052.5	1052.5	79.6	0	0
1999	NO6	545.8	1323	485.5	837.5	837.5	63.3	0	0
1999	CO10	545.8	1323	375.9	947.1	947.1	71.6	0	0
1999	CE9	545.8	1323	472.7	850.3	850.3	64.3	0	0
1999	CE5	545.8	1323	817.8	505.2	505.2	38.2	0	0
1999	NE3	545.8	1323	702.8	620.2	620.2	46.9	0	0
1999	NE8	545.8	1323	388.4	934.6	934.6	70.6	0	0
1999	NO4	545.8	1323	493.3	829.7	829.7	62.7	0	0
1999	PR2	545.8	1323	665.4	657.6	657.6	49.7	0	0
1999	PR7	545.8	1323	769.9	553.1	553.1	41.8	0	0
1999	CO1	545.8	1323	724.1	598.9	598.9	45.3	0	0
2000	Mosa26	405.5	983	58	925	925	94.1	0	0
2000	Mosa13	405.5	983	126	857	857	87.2	0	0
2000	Mono	405.5	983	631.5	351.5	351.5	35.8	0	0
2000	NO6	405.5	983	204	779	779	79.2	0	0
2000	CO10	405.5	983	318	665	665	67.7	0	0
2000	CE9	405.5	983	365	618	618	62.9	0	0
2000	CE5	405.5	983	306	677	677	68.9	0	0
2000	NE3	405.5	983	513.5	469.5	469.5	47.8	0	0
2000	NE8	405.5	983	338	645	645	65.6	0	0
2000	NO4	405.5	983	242	741	741	75.4	0	0
2000	PR2	405.5	983	341.2	641.8	641.8	65.3	0	0
2000	PR7	405.5	983	496	487	487	49.5	0	0
2000	CO1	405.5	983	453	530	530	53.9	0	0
2000	DM1	405.5	983	521.8	461.2	455	46.3	6.25	0.64
2000	DM2	405.5	983	464.2	518.8	517.5	52.6	1.31	0.13
2000	DI5	405.5	983	718.2	264.8	263.3	26.8	1.46	0.15
2000	DI6	405.5	983	618.8	364.2	363.7	37.0	0.53	0.05
2000	SM3	405.5	983	462.7	520.3	520.1	52.9	0.23	0.02
2000	SM4	405.5	983	443	540	537.8	54.7	2.24	0.23
2000	SI7	405.5	983	341.9	641.1	641	65.2	0.12	0.01
2000	SI8	405.5	983	398.4	584.6	584.1	59.4	0.52	0.05
2001	NO6	497.3	1205	340.5	864.5	864.5	71.7	0	0
2001	CO10	497.3	1205	267.5	937.5	937.5	77.8	0	0
2001	CE9	497.3	1205	156.5	1048.5	1048.5	87.0	0	0
2001	CE5	497.3	1205	247.3	957.7	957.7	79.5	0	0
2001	NE3	497.3	1205	416.5	788.5	788.5	65.4	0	0
2001	NE8	497.3	1205	418	787	787	65.3	0	0
2001	NO4	497.3	1205	135	1070	1070	88.8	0	0
2001	PR2	497.3	1205	67.5	1137.5	1137.5	94.4	0	0
2001	PR7	497.3	1205	317	888	888	73.7	0	0
2001	CO1	497.3	1205	603	602	602	50.0	0	0

[1]calculated from mean cob yield in 1999, estimated from rainfall-yield curves for 2000 and 2001

4.4.2.2 Relationship between yield loss and damage at planting

Seasonal variations (Appendix 8 & 9) are the major factors causing yield variation in maize production (Norman *et al.*, 1984). In this study, in some years (e.g. 1999 and 2000), when rainfall was well distributed (Fig. 27), the relationship between percentage damage and percentage yield loss was positively correlated when the data for all the fields were lumped together (e.g. 1999, $r = 0.66$, $n = 13$, $p=0.014$ and 2000, $r = 0.73$, $n = 21$, $p=0.035$) (Fig. 28). When rainfall was poorly distributed throughout the growing season (i.e. in 2001), there was no relationship between damage at planting and yield loss. Therefore, when rainfall is well distributed throughout the growing season, rodents become a key factor in determining yield loss as a result of damage at planting. Similar observations were made by Metcalf and Thomas (1966) and Samol (1972) in other crops such as sugar cane and Key (1990) in maize.

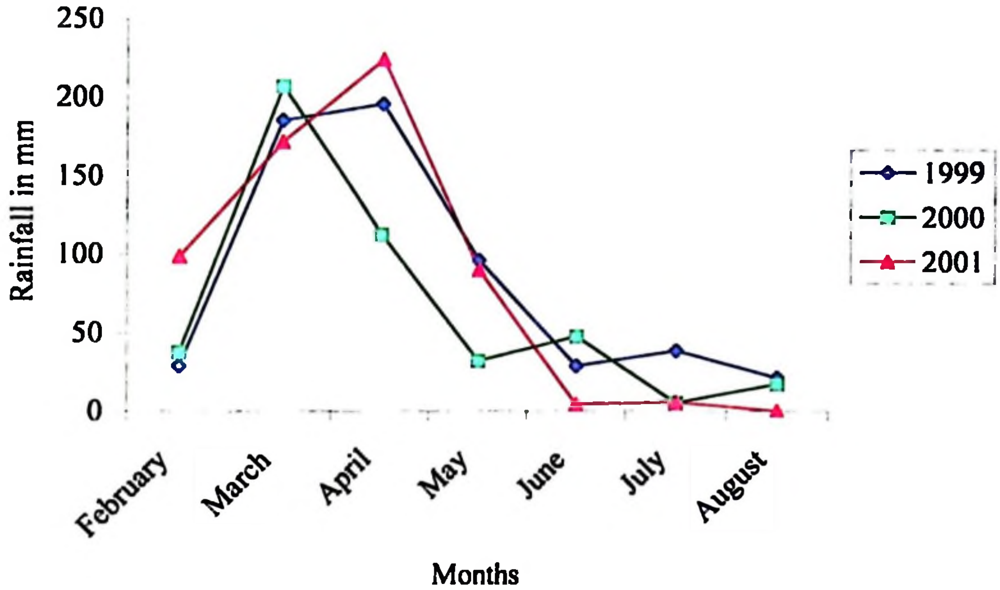


Figure 27: Rainfall patterns during the long rains maize planting seasons for 1999 - 2001.

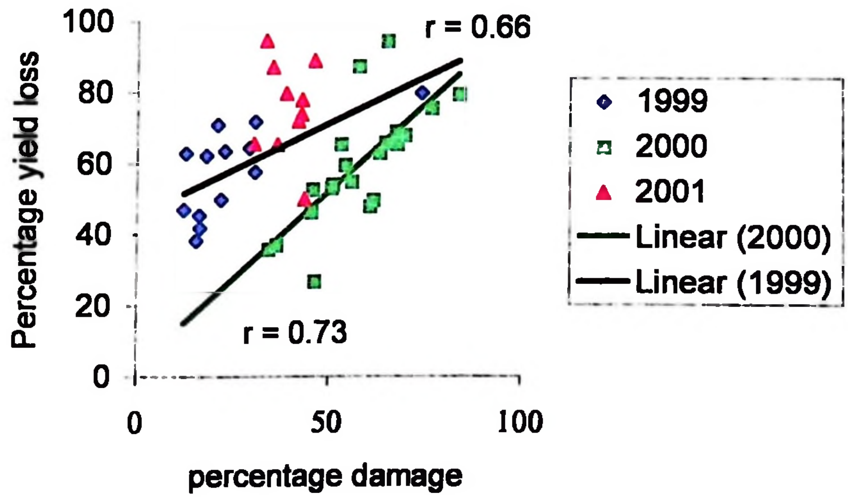


Figure 28: Correlation between percentage damage and yield loss.

Yield loss and rodent damage at planting also varied according to treatment. In the MOSA fields, yield loss and maize damage at planting were highly and positively correlated (Fig. 29). However, when rainfall was poorly distributed in the cropping season, the correlation was weak (Fig. 30).

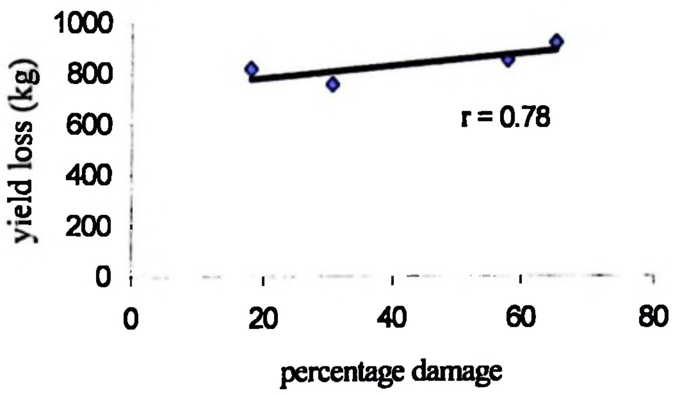


Figure 29: Correlation between rodent damage at planting and estimated yield loss before harvesting time for two MOSA fields in 1999 and 2000.

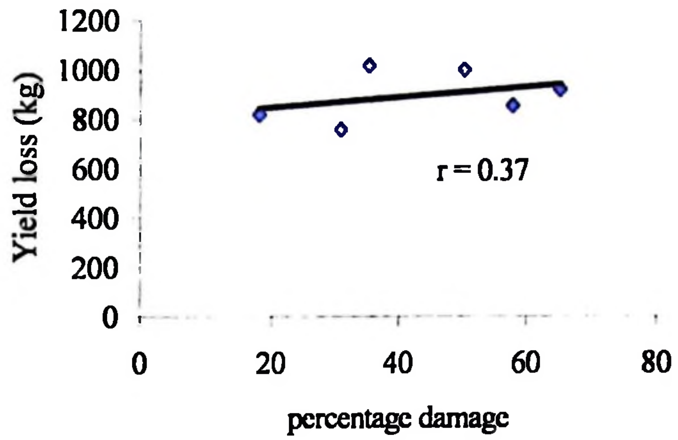


Figure 30: Correlation between damage at planting and estimated yield loss before harvesting time for two MOSA fields for 1999 to 2001.

The relationship between yield and rainfall has been reported by various authors (Seif and Pedersen, 1978; Cornich *et al.*, 1980; and French and Schutz, 1984). For maize, fairly uniform rainfall distribution throughout the growing period is important (Norman *et al.*, 1984). The cumulative rainfall in March to July 2001 was higher than in 2000, but the rainfall terminated early in May during the flowering period (Fig. 27), which led to high yield loss. It has long been recognised that maize is particularly sensitive to water deficit at flowering (Salter and Goode, 1967). Drought reduces leaf area, leaf photosynthetic rate (during the stress period, although leaves may recover completely), delays silking and reduces grain yield components, particularly grain number (Hall *et al.*, 1980). The reduction in grain number appears to be due to increased asynchrony in flowering: water deficit reduces the rate of pollen production during the period silks are receptive and reduces the period when silks are exposed to pollen, but does not affect pollen viability (Herrero and Johnson, 1981). Therefore, erratic and not fairly uniform distributed rainfall contributes to high yield loss in maize (Herrero and Johnson, 1981).

When other factors are favourable, particularly rainfall, rodent damage is a key factor in causing yield loss in maize at the seedling stage. Estimates of yield loss caused by rodents at harvest appear to vary considerably. In maize, unlike rice, cotton, or millets and sorghum, there is a minimal compensation (Myllymäki, 1987). Myllymäki (1987) reported that below 20% rodent damage, the farmer gets better returns both in terms of money and labour, but above this level, replanting becomes a more profitable strategy for maize production. However, this will be true only if the spatial distribution of damage is not clustered in the field.

4.4.2.3 Relationship between rodent density and yield loss at planting

In fields cultivated by tractor; those planted with maize and surrounded by fallow land and fields planted with maize, enclosed by iron sheets to prevent escape of rodents within and entry of rodents from outside, rodent density and yield loss were positively correlated (Fig. 31). It is assumed that the different treatments in the fields affected the rodent density differently, and therefore each one was a different entity.

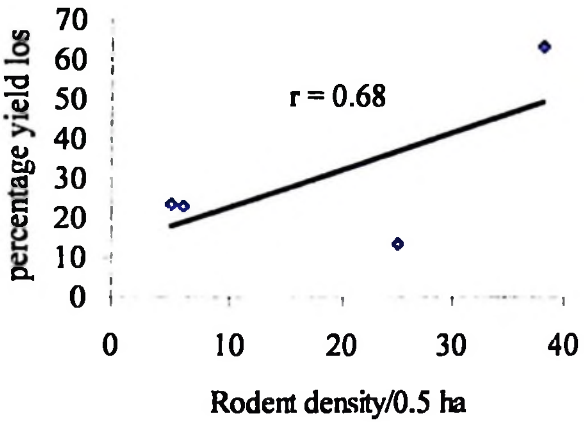


Figure 31: Correlation between rodent density and yield loss in tractor ploughed fields.

Farmers realize that a high population of rodents at the time of planting can cause severe losses because of the retrieval of the seed from the ground and cutting of the seedlings as they emerge (Mwanjabe and Leirs, 1997). In the current study, the relationship between rodent density and rodent damage clearly suggests that unless the rodent populations is reduced to very low levels, serious damage will occur.

4.4.3 Relationship between rodent density and maize cob damage at maturity

Table 17 shows maize cob damage and the resultant yield loss. Few cobs were damaged in the fields and therefore, yield loss at maize maturity was not significant. There was no cob damage in most of the fields except in the Mazimbu fields, but the yield loss was mostly below 1%.

Table 17: Cob damage by rodents and the resulting yield loss at maturity stage of maize crop.

Year	Field	%cob damage	Expected yield (kg)	Actual yield (kg)	Yield loss (kg)	Yield loss at maturity	% yield loss at maturity
1999	Mosa26	0	1323	563.1	759.9	0	0
1999	Mosa13	0	1323	502.4	820.6	0	0
1999	Mono	0	1323	270.5	1052.5	0	0
1999	NO6	0	1323	485.5	837.5	0	0
1999	CO10	0	1323	375.9	947.1	0	0
1999	CE9	0	1323	472.7	850.3	0	0
1999	CE5	0	1323	817.8	505.2	0	0
1999	NE3	0	1323	702.8	620.2	0	0
1999	NE8	0	1323	388.4	934.6	0	0
1999	NO4	0	1323	493.3	829.7	0	0
1999	PR2	0	1323	665.4	657.6	0	0
1999	PR7	0	1323	769.9	553.1	0	0
1999	CO1	0	1323	724.1	598.9	0	0
2000	Mosa26	0	983	58	925	0	0
2000	Mosa13	0	983	126	857	0	0
2000	Mono	0	983	631.5	351.5	0	0
2000	NO6	0	983	204	779	0	0
2000	CO10	0	983	318	665	0	0
2000	CE9	0	983	365	618	0	0
2000	CE5	0	983	306	677	0	0
2000	NE3	0	983	513.5	469.5	0	0
2000	NE8	0	983	338	645	0	0
2000	NO4	0	983	242	741	0	0
2000	PR2	0	983	341.2	641.8	0	0
2000	PR7	0	983	496	487	0	0
2000	CO1	0	983	453	530	0	0
2000	DM1	3.31	983	521.8	461.2	6.25	0.64
2000	DM2	0.78	983	464.2	518.8	1.31	0.13
2000	DI5	0.13	983	718.2	264.8	1.46	0.15
2000	DI6	0.39	983	618.8	364.2	0.53	0.05
2000	SM3	0.16	983	462.7	520.3	0.23	0.02
2000	SM4	1.10	983	443	540	2.24	0.23
2000	SI7	0.29	983	341.9	641.1	0.12	0.01
2000	SI8	0.27	983	398.4	584.6	0.52	0.05
2001	NO6	0	1205	340.5	864.5	0	0
2001	CO10	0	1205	267.5	937.5	0	0
2001	CE9	0	1205	156.5	1048.5	0	0
2001	CE5	0	1205	247.3	957.7	0	0
2001	NE3	0	1205	416.5	788.5	0	0
2001	NE8	0	1205	418	787	0	0
2001	NO4	0	1205	135	1070	0	0
2001	PR2	0	1205	67.5	1137.5	0	0
2001	PR7	0	1205	317	888	0	0
2001	CO1	0	1205	603	602	0	0

The damage caused by rodents to maize cobs at maturity stage was less severe than at the seedling stage when it was more extensive. Key (1990) reported more extensive damage of seeds than cobs in maize by squirrels. At maturity stage of the cobs, more than one rodent could damage a cob for several days, but the yield loss is insignificant compared to removal of seeds and seedlings. Funmilayo and Akande (1977) also reported that the damage caused by rodents at maturity stage of maize is small except when several species are involved and numbers are high. Taylor and Green (1976) reported that although rodent reproduction mainly takes place during the period when cereals and seeds are the major food sources, for maize in particular, damage at maturity stage, is low. In terms of rodent management at maturity stage of maize, the crop should be harvested early.

Rodent damage in maize fields showed two basic patterns, one superimposed upon the other (Mwanjabe P.S. personal communication, 2001). The first is chronic damage, which occurs every year in many areas and may be highly variable between fields and locations (Mwanjabe *et al*,. 2002). This type of pattern occurred during the course of the study. However, the local chronic losses can be much higher in some years, particularly when crops are grown in areas highly susceptible to rodent damage. The second pattern, is associated with rapid increases in the numbers of rodents over wide areas, but it is sometimes localised in some regions (Fiedler, 1988).

Outbreaks resulting from unusual rodent population increases can be dramatic and extremely visible and can occasionally result in food shortages over large areas (Fiedler & Fall, 1994; Leirs, 1999). These two patterns of rodent populations have different impacts on the crop and different magnitudes of crop loss. The current study clearly shows that the critical determinants of crop loss due to rodents is damage at planting time and seedling stage. Controlling rodents to lower rodent density at planting and seedling stage is an important management strategy.

4.5: Simulation Model

4.5.1 Preliminary simulations

Rodent control is only viable if it results in a net economic gain for the farmers. To determine which control methods will be most cost-effective and the optimal timing for control, Skonhoft *et al.* (In press) developed a bio-economic modelling system. In Skonhoft *et al* (In press) model, hyperbola function of two years data was used. However, in the current study, a sigmoid function of three years data was used. In order to appreciate the basic logic of the numerical simulations, Figure 32 provides two examples based on one rainfall series and two different control strategies in which control is applied twice a year in February and November, and no control. When control is applied, rodent numbers remain low, whereas the annual harvest as well as the current net profit are higher than in the case of no control. This indicates that it is economically beneficial to control the rodent population as compared to no control action.

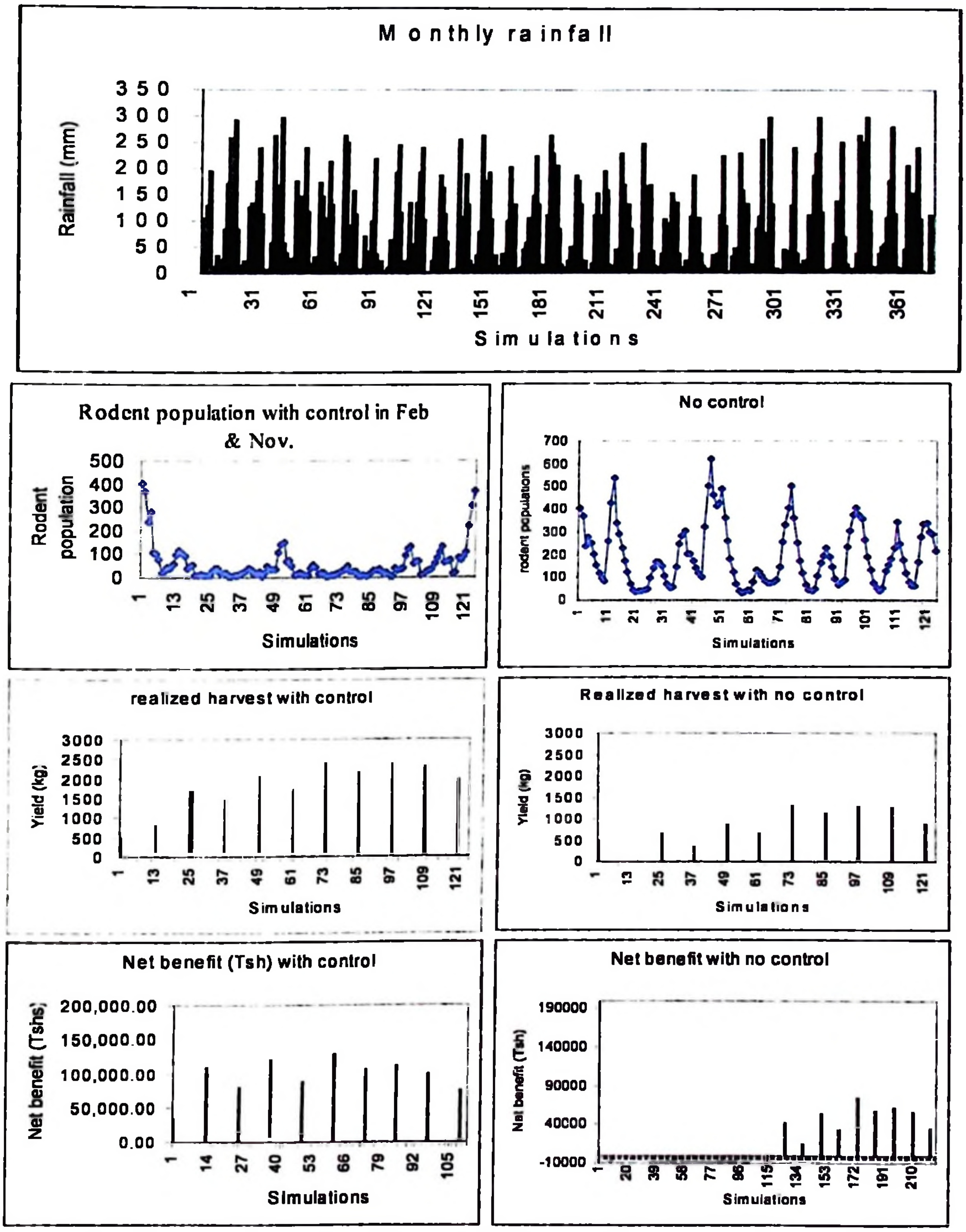


Figure 32: Two examples of model runs (with resulting graphs for rainfall, rodent populations, realized harvest, and net benefit) under two different control strategies; control applied in two months (February and November) each year and no control.

4.5.2 Duration, timing and other control strategies

One hundred and twenty nine different control strategies were run by changing the months in which control was applied (see Appendix 10). Tables 18 summarizes the simulation results for the ten most rewarding economic strategies, for calendar strategies (control after planting in March, control at harvest in July or both), and for cases where control was always applied, or never applied, as well as for a situation in which there are no rodents. The results show that combinations of 2-3 months control in the period before the start of the cropping season are the most rewarding.

In general, the median present-value is low without control (0 months), but increases for strategies with up to 4 consecutive months of control, beyond which the present-value starts decreasing (Appendix 10). The most rewarding combination of rodent control months is February and November. Therefore, only the results for strategies with up to 5 consecutive months are shown in the Appendix 10. The results of this study also show that controlling rodents in all months of the year gives a low present value (Table 18). Continuous killing of rodents throughout the year can result to low population of rodents or even rodent extermination (Stenseth *et al.*, 2001), but the present value becomes lower because the gain is less than the cost of control as compared with when rodents are controlled in specific months. Similar observations were reported by Flint and Bosch (1987) for insect pests.

This study clearly illustrates that for given baseline values of prices and costs, rodent control is economically rewarding since the present value is higher when control is carried out in certain months, but not similar to the current calendar for rodent control (i.e. controlling in March, July or both). The model shows that it is more profitable to control rodents in January and February than in other months, whereas if rodenticides are applied two months every year, the most rewarding is to start control activities in November and February, followed by October and February (Appendix 10). If rodenticides are applied for 3-5 months, it is most rewarding to start control activities in July to December/January.

Table 18: Ranking of the 10 most economically rewarding strategies given by timing and length of control.

Ranking	Timing	Length	Present value (Tshs)		
			Median	Lower	Upper
	No rodent		1,120,606	996,757	1,260,835
1	February-November	2	931,014	773,896	1,075,264
2	February-October	2	878,199	719,371	1,052,676
3	August-September-November	3	838,413	697,512	987,665
4	July-August-November	3	816,851	634,975	974,015
5	September-October-December	3	813,120	648,320	985,674
6	August-November	2	808,682	600,792	978,686
7	July-August-October	3	782,070	633,179	978,902
8	August-September-December	3	779,424	588,025	984,545
9	January-November	2	777,642	576,058	974,042
10	January-February-November	3	774,406	645,634	914,663
	No Control		365,138	243,547	513,338
11	July	1	322,608	186,692	476,103
12	March	1	250,907	133,913	399,486
13	March-July	2	230,353	98,824	513,825
14	Controlling all the months throughout the year	12	37,512	-86,344	117,742

The hypothetical case of no control of rodents (upper line), symptomatic treatment months and control each month (lower line), are included as well. Present value (in Tshs) is presented by the median and the lower (0.025) and upper (0.975) percentile for the 100 simulations performed for each strategy.

4.5.3 Comparison between the current calendar control and the most ten rewarding economic strategies

The current calendar treatment is a strategy for rodenticide use, that is applied by many farmers in Tanzania (Myllimäki, 1987). It represents an ad-hoc approach (farmers are reactive rather than palliative), and typically rodenticides control is applied when damage is high during planting season, or just before harvest (Mwanjabe, 1993; Makundi *et al.*, 1999). The results in Table 18 show that the ad-hoc control strategies (i.e. applying rodenticides in March, July or both) have low present value (PV) compared with the most ten rewarding control strategies. The strategy of no control has high PV than if ad-hoc control strategies are used. The PV becomes less when rodenticide application is undertaken throughout the year (Table 18). The control strategies using such calendar treatment are not economically viable strategies because the control costs do not compensate for the reduced damage, hence it gives low present value to a farmer. In fact, *M. natalensis* are secretive and nocturnal, therefore, when they are seen, damage is already severe and crop losses may be high.

From this study, therefore, the economically most rewarding strategies differ from current calendar treatment when severe rodent damage is noticed in either March, July or both. Generally, the results show that poisoning rodents will be most rewarding just before the cropping season begins in order to reduce the number of rodents before planting maize seeds. Hence, minimizing the population during planting is enough to reduce total yield losses at harvest (Mulungu *et al*., 2003). In this study, the simulations show net profit differences between various combinations of control months towards the start of the planting season. Therefore, shifting from the current calendar treatment practices to most rewarding calendar treatment to control rodents can probably improve the economic returns of maize production in Tanzania substantially.

Models, however, have a major limitation of being unable to include all factors affecting production (Rwamugira, 1996). The present model has some weakness due to five major assumptions. The first is that the model does not include the common practice of Tanzanian farmers to replant after rodent damage. Therefore, the model assumes no replanting takes place after rodent damage.

Secondly, the present model does not yet include rodent dispersal. Therefore, it only assumes local reproduction of rodents. It is obvious that rodent dispersal can play an important role in crop damage, particularly when rodent densities after control have become much lower within the crop than in the surrounding fields (Leirs *et al*., 1997b). The third assumption is that the model uses discrete time steps of one month; however, a lot can happen in a rodent population in one month and a population may even be capable of recovering from rodenticide application in the course of a few weeks. The fourth assumption is that the model uses the accumulation of rainfall from planting to harvesting. In reality, the model should incorporate the distribution of rainfall in the whole cropping season. In years with good rainfall distribution, the yield is also high. The fifith assumption is that the price of maize is fixed. In fact, it changes depending on seasons. Immediately after harvest the price of maize is low compared with the price of maize during the planting season.

The sixth assumption of a model is that rodent control has no effect on the juveniles because they are just born and still in the nest and will not eat the poison. In fact if the mother was killed during a control operation then none of these young would survive.

Therefore, the model should be used very cautiously in concrete situations. However, the main finding of the current study is that applying rodenticides prior to maize planting time in certain months instead of when the pest or damage is seen, will probably hold and is clearly an application rule that is quite easy to implement.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study has revealed that:

1) The spatial distribution of rodent damage to maize was random when the fields were located between other maize fields. Damage distribution was dependent on the cropping pattern.
2) Non-stratified systematic row sampling technique is the most robust for determining damage and yield losses at different crop growth stages, and is the simplest to use. Stratified estimation techniques perform poorly because it is difficult to properly recognise the strata in the field.
3) The developed standard curve shows the sampling row interval for obtaining a desired accuracy and what level of accuracy can be expected for a given sampling row interval for non-stratified systematic row sampling technique. The regression line shows that the variation of an estimate stays below 10% of the actual damage when a sampling interval of less than 6 rows is used.
4) The relationship between rodent density and percentage damage is a sigmoid function, in which at low rodent density there is a direct relationship (linear) with maize damage. However, it reaches an asymptote (40 rodents per 0.5 ha) where no further increase in either percentage damage regardless of increases in rodent density.

5) Rodent damage at planting and yield loss are strongly correlated only in years with well distributed rainfall. In years with poor rainfall distribution no correlation was found.

6) Two months of control just before planting season (January and February or November and February or October and February) is the best overall strategy. The economically most rewarding strategies differ significantly from current practices of symptomatic treatment when severe rodent damage is noticed in either March or July. Therefore, shifting from symptomatic practices and controlling rodents on a calendar basis can substantially improve the economic conditions for the majority of maize producing farmers in Tanzania in similar conditions as those of study sites in Morogoro.

5.2 RECOMMENDATIONS

(1) Rodent population density at seedling stage is a critical factor which influences yield losses. In this study, much of the resultant yield loss at crop maturity was not accounted for by variation in rodent damage at planting. More studies are therefore, necessary to identify the factors that interact with rodent damage to cause total yield loss at harvest

(2) The present study is based on two sites which are in a similar agro-ecological zone. Therefore, one cannot make generalizations for all agro-ecological zones or entire country. Therefore, this study should be repeated in other affected agro-ecological

zones characterized by rodent outbreaks for comparisons

(3) The current model should be further tested after incorporating (1) replanting after rodent damage (2) rodent dispersal factor (3) distribution of rainfall instead of accumulation of rainfall from planting to harvesting (4) fluctuations of maize price instead of a fixed price and (5) the effect of poison on juveniles.

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7.0 APPENDICES

Appendix 1: Rats invade maize farm in Kwale District Kenya

News
Daily Nation Newspaper, Monday, May 7, 2001

Rats invade maize farms

By KAULI MWATELA

Rats have invaded Kwale District, destroying more than 30,000 acres of maize.
Ministry of Agriculture officials in Kwale and Mombasa yesterday confirmed that rats had invaded Msambweni, Kubo, Kinango and Samburu divisions. "It is true that rodents have invaded Kwale District and are destroying seeds and crops," the official, who asked not to be named, said. He did not, however, say what measures were being taken to control them.
Farmers yesterday called upon the government to intervene and control the rats in order to boost food production. Addressing a farmers' meeting at various places yesterday, local councillors warned that the district would face famine if the government did not control the pests. Speakers blamed Agriculture officials for failing to give proper information to farmers on the pests. The councillors, Mr Thomas Mwangeka, Mr Iddi Gambari, Mr Chirupi Sirisiri, Mr Hassan Chetembe, Mrs Susan Mbulwa Nzuki, Mr Hamisi Benzao and Mr Matano Chimoche, asked the permanent secretary in the Ministry of Agriculture to visit the district.
"The rodent invasion has demoralised farmers. We ask the government to intervene and assist them with seeds and chemicals to combat the problem. Otherwise, Kwale people will starve," Mr Mwangeka said. The affected locations include Mwereni, Dzombo, Kikoneni, Ndavaya, Mkongani, Mangawani, Mwavumbo and Puma. A farmer, Mr John Kamanza, told the meeting that his 10 acres of maize was destroyed by the rodents. "I have no seeds and I am appealing to the government to assist me. The government is my only hope," Mr Kamanza told the meeting at Mwereni.
The farmers said the rats were more destructive than army worms. They said they have reported the matter to Agriculture officials but no action had been taken. "Agriculture officers should not sit in their offices and give their bosses wrong information. They should instead tour our areas and prove us wrong," Mr Mwangeka said. They said the district could not participate in development activities following the destruction of the food crops by the rodents.

Appendix 2: Rodent outbreak in Coast Region of Tanzania.

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AGRICULTURE-TANZANIA: Maize Crop Devastated
By Rats
By Paul Chintowa

DAR ES SALAAM, Feb 23 (IPS) -- Rats moving in groups of up to 1,000 have invaded Tanzania's Indian Ocean coast, eating up hundreds of square kilometres of maize, the country's staple crop. Scientists say the rats, which have bred and multiplied in large numbers as a result of heavy rains in recent months, can consume up to 50 percent of the crop produce an hectare, after invading a farm. Bakhet Kilonzo, head of the rodents central unit at Tanzania's Sokoine University of Agriculture in Morogoro, some 200 kilometres west of the capital Dar es Salaam, says the rodents invasion is the largest in 40 years. He warns that Tanzania is bracing for another major outbreak in the crucial August-September short-rain period.

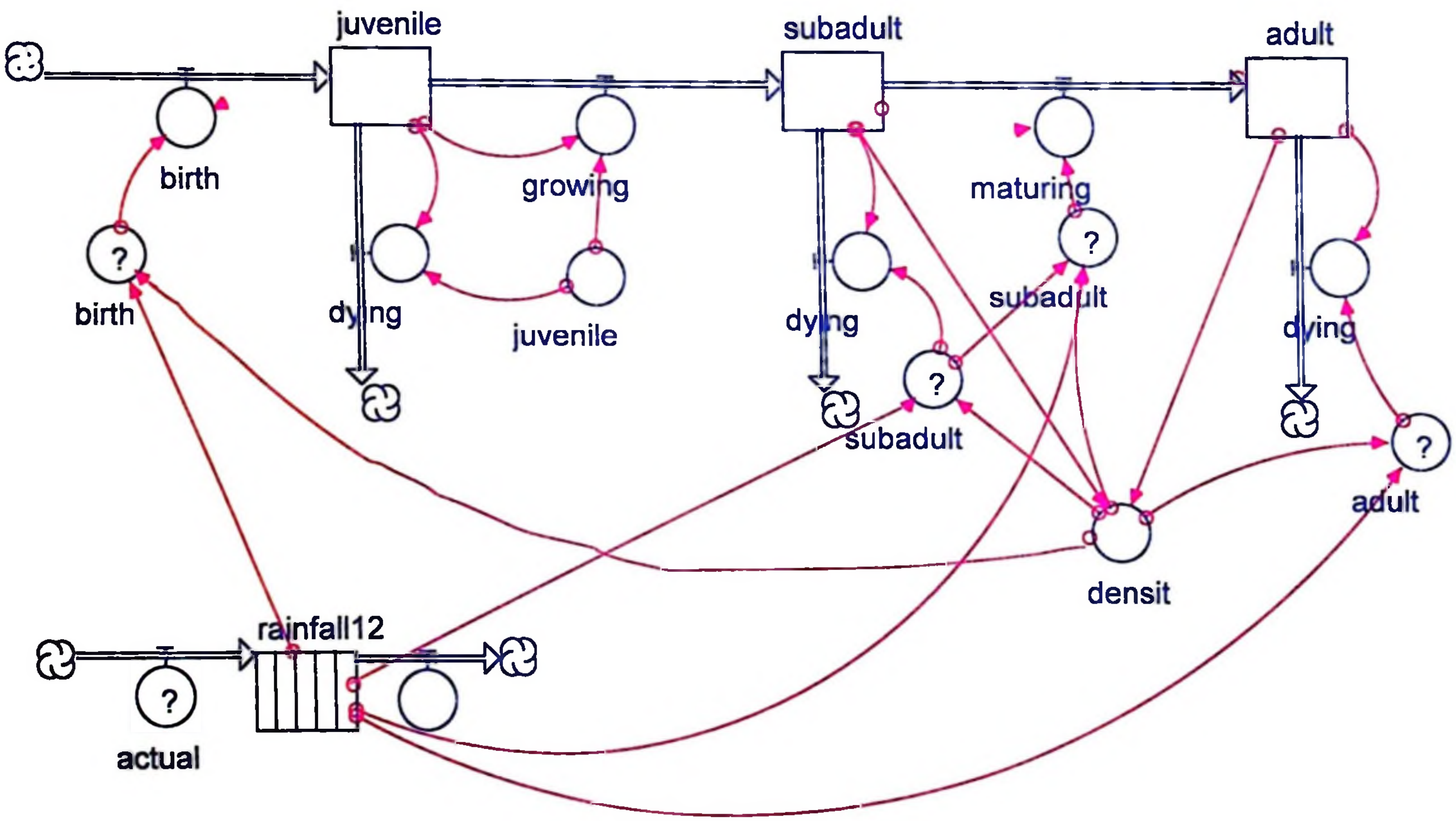
According to Kilonzo, the breeding rate of the rats is much higher during heavy rains and flooding. Expressing his concern, Paul Kimiti, who is Tanzania's Minister for Agriculture and Cooperative, has described the invasion by the rodents as bad news for the East African country. "Nearly 100,000 hectares (of maize) have been devastated by the rodents in seven regions. We don't expect any miracle this year," Kimiti told IPS. Kilonzo, who has done research on the rats in seven of Tanzania's 20 regions, says the rodents attack maize cobs before they are ripe. The 100,000 hectares destroyed so far were planted during last October-December rainy season. The rats have come at a bad time for Tanzania. Last year drought placed nearly four million on the brink of a severe food shortage, prompting the government to appeal to the international community last April for about 81.3 million U.S. dollars to alleviate the situation.

This year's harvest is expected to reach a mere 700,000 tonnes, which is just about a third of what it should be -- annual production in 1993-1995 averaged 2,336 million tonnes, according to the United Nations Food and Agriculture Organisation (FAO). As a result of the reduction, the government has had to appeal for emergency aid. It says it needs 100,000 tonnes of food between now and July, when farmers will start harvesting their crops. Maize accounts for the bulk of the 4.41 million tonnes cereal requirements which also includes sorghum, pulses, plantains (cooking bananas), rice and tubers. "This year has been the worst.I have never seen anything like it in my lifetime," said Marriot Kalanje, executive director of the Tanzania Chamber of Commerce, Industry and Agriculture. Kalanje told IPS recently that the continuing floods have caused up to 30 percent losses or more of some agricultural crops. The hardest hit are cotton and coffee, Tanzania's key export crops.

All sectors of the economy have been hit, and the government is still trying to estimate the overall damage caused by the floods attributed to the El Nino phenomenon. The rodent invasion is hurting farmers. One farmer, Mwanaisha Hamsa, from Chalinse, some 120 kilometres west of here, appears desparate. "I am in dire need of food. Look at my farm. It has been devastated by rodents," he says. The government says it is overstretched to tackled the plague. The FAO has sent a team to study the damage caused by the rodents. Kilonzo says the university is taking some precautionary measures to ensure that the rodents don't pose a threat to human health. "We are researching if the rodents are harmful or not. We don't want to be taken unaware," he says. Such speculations are already rife in Tanga region, which has been described by German colonial administrators as the "Switzerland of Africa", because of its favourable weather conditions. An outbreak of a mysterious plague there, which some attribute to rodents, is causing concern in Tanzania.

Between April 1980 and March last year, some 594 people in Tanga's Lushoto district were killed by the plague, while 7,033 were treated for the illness. Lushoto is famous for its fruits and vegetable production, almost half the total need of the country. "The fruits and vegetable farms there are an ideal habitat ground for rats," according to Kilonzo. Besides the rodents, media reports say locusts have been spotted in the central regions of Dodoma and Singida.(END/IPS/PC/MN/PM98)

Appendix 3: Model with density dependent and density independent for survival and reproduction of *Mastomys natalensis*



Appendix 4: Summary of monthly weather data for 1999 to 2001 in Morogoro, Tanzania.

Year	Month	Total rainfall (mm)	Mean radiation (MJ-2)	Total pan evaporation (mm)	Mean temperature (^0C)	
					Maximum	Minimum
1999	January	116.10	19.89	216.50	33.4	22.3
	February	29.00	21.88	201.60	33.8	21.8
	March	185.70	16.50	149.60	30.3	21.8
	April	196.30	15.06	100.20	28.6	20.6
	May	96.30	14.28	97.70	28.9	19.4
	June	28.80	15.01	87.80	27.6	16.4
	July	38.70	14.28	91.80	26.5	18.2
	August	21.40	13.43	86.90	28.7	16.7
	September	16.10	17.99	140.60	29.6	22.3
	October	11.50	19.22	182.50	30.9	18.8
	November	35.70	20.17	228.20	32.8	19.8
	December	60.90	17.38	168.40	31.6	20.5
2000	January	68.80	22.60	219.80	33.1	21.4
	February	37.90	23.60	224.40	31.7	21.3
	March	207.40	17.57	127.40	31.0	20.0
	April	113.10	16.07	100.00	30.8	19.9
	May	32.00	14.98	90.80	28.5	19.0
	June	47.80	15.06	92.80	27.9	17.4
	July	5.20	15.13	109.70	27.1	15.9
	August	17.30	15.49	133.20	28.4	17.0
	September	4.10	17.09	164.10	29.8	17.2
	October	0.00	20.17	220.00	32.4	18.6
	November	49.40	18.06	226.90	33.0	21.4
	December	207.00	17.39	162.50	30.9	21.6
2001	January	104.30	16.99	139.20	30.4	21.7
	February	99.00	20.23	137.80	29.1	21.2
	March	171.90	20.37	149.70	31.3	22.1
	April	224.60	16.78	105.10	29.7	21.7
	May	90.40	15.48	88.70	28.7	19.8
	June	4.60	15.62	85.60	27.7	17.0
	July	5.80	14.59	86.40	26.4	15.7
	August	Trace	17.81	138.00	28.5	16.2
	September	0.00	18.67	159.10	29.3	17.1
	October	11.10	20.21	192.70	31.4	18.5
	November	0.00	21.43	229.50	33.7	20.3
	December	72.30	22.00	239.70	33.2	22.6

Source: Meteorology station, Sokoine University of Agriculture, Morogoro, Tanzania

Appendix 5: Calculating proportional cob damage at maturity.

(a) Longitudinal cob damage

For longitudinal damage of a cob, the proportion damage was calculated as the ratio of the area of damaged portion (i.e. length of damaged portion * width) and the area of ear. It was assumed that, the shape of the ear is similar to that of cylinder. Therefore, the area is equal to π * diameter (i.e. circumference) * length of an ear, which was the length of the fully developed kernels on the ear from bottom to top (i.e. πDL). The diameter of ear was measured using Venier callipers, whereas the length and width were measured using tape measure in centimetres.

In summary:

$P_l = A_1/A_2$..[1]

where:

P_l = damaged proportion by longitudinal damaged of ear

A_1 = the damaged portion (length * width) cm^2, and

A_2 = Area of ear (πrl) cm^2.

(b) Circular cob damage

For circular ear damage, the damaged portion was calculated as ratio of the length of damage (i.e. which is the average of the shortest and the longest lengths of portion damaged) and the length of ear.

In summary:

$P_c = l_1 + l_2/2L$..[2]

where:

P_c = damaged proportion by circular damage of ear

l_1 = shortest length of damaged portion (cm),

l_2 = longest length of damaged portion (cm), and

L = length of ear (cm), which was the length of the fully developed kernels on the ear,

If the damaged portion was perfect circular (i.e. no difference in damaged portion) then the proportion cob damage was calculated as ratio of the length of damage portion and the length of ear.

In summary:

$P_c = l/L$..[3]

where:

P_c = damaged proportion by circular damage of ear, l = length of damaged portion (cm),

L = length of ear (cm), which was the length of the fully developed kernels on the ear,

The damaged proportion of ears per field was calculated as the ratio of the total damaged portions and the number of ears per sample in that field.

Appendix 6: Monthly demographic parameter values for each of the combined rainfall-density regimes in the population dynamics model. The values for s_{0n} and s_{0w} are arbitrarily set, the other values were obtained from demographic analysis (from Leirs *et al.* 1997).

Regime definition							
Rainfall in the past 3 months (mm)	V_n	<200	<200	200-300	200-300	>300	>300
Density per ha	$N^{(e)}_n$	>150	<150	>150	<150	>150	<150
Demographic rates							
Net reproductive rate	$B(V_n, N^{(e)}_n)$	1.29	5.32	0.30	6.64	4.69	5.82
Juvenile survival in the nest	s_{0n}	1.0	1.0	1.0	1.0	1.0	1.0
Juvenile survival after weaning	s_{0w}	0.5	0.5	0.5	0.5	0.5	0.5
Subadult survival	$S_1(V_n, N^{(e)}_n)$	0.629	0.513	0.682	0.617	0.678	0.595
Subadult maturation	$\psi(V_n, N^{(e)}_n)$	0.000	0.062	0.683	0.524	0.155	1.000
Adult survival	$S_2(V_n, N^{(e)}_n)$	0.583	0.650	0.513	0.602	0.505	0.858

Appendix 7: Baseline values prices and costs (1999-prices Morogoro, Tanzania),damage function and other parameters

Description	Parameter	Default value
Economic parameters		
Net price maize	P	100 Tsh/kg
Price fertiliser	Q	220 Tsh/kg
Price poison	W	6500 Tsh/kg
Fixed costs per ha maize field	K	10 000 Tsh/ha
Planning horizon	T	10 Yrs
Discount rate	δ	0.07
Damage at planting		
Background death rate of seedlings	A	0.0827
Maximum proportion of seedlings damaged	B	0.8339
Rodent population size at half of maximum damage	C	36.068
Damage before harvesting		
Amount damaged by 1 multimammate rat during 30 days	D	0.270 kg
Other		
Fertiliser per ha	F	40 kg
Amount of poison used per ha	X	2 kg

Appendix 8: Matrix of correlation coefficients between yield loss due to damage at planting and environmental factors throughout the growing season of maize.

Variable	1	2	3	4	5
1. Yield loss	1				
2. Damage	0.53	1			
	p=0.000				
3. Rainfall	-0.22	-0.76	1		
	p=0.1437	p=0.000			
4. Radiation	0.55	0.30	-0.29	1	
	p=0.000	p=0.45	p=0.051		
5. Temperature	0.33	0.76	-0.98	0.49	1
	p=0.27	p=000	p=0.00	p=0.001	

Appendix 9: Summary of stepwise regression, variable: yield loss due to damage at planting using Forward stepwise.

	Forward stepwise, p to enter: 0.05; p to remove: 0.05						
Effect	Steps	Df	F to remove	P to remove	F to enter	P to enter	Effect status
Damage	Step 1	1			17.18216	0.000152	Out
Rainfall		1			2.29699	0.136776	Out
Radiation		1			18.60795	0.000089	Entered
Temperature		1			5.21400	0.027290	Out
Radiation	Step 2	1	18.60795	0.000089			In
Rainfall		1			0.28319	0.597360	Out
Damage		1			11.51763	0.001491	Entered
Temperature		1			0.28319	0.597360	Out
Radiation	Step 3	1	12.78811	0.000878			In
Damage		1	11.51763	0.001491			In
Rainfall		1			9.16287	0.004208	Entered
Temperature		1			9.16287	0.004208	Out
Radiation	Step 4	1	17.58984	0.000138			In
Damage		1	22.44254	0.000025			In
Rainfall		1	9.16287	0.004208			In
Temperature		0			-	-	Out

Appendix 10: Ranking of the 129 most economic rewarding control strategies given by timing and length (total number of months of the control). The hypothetical case of no rodents (upper line) and the case of control in all the months throughout the year (lower line). Present value (in Tshs) is presented by the median and the lower (0.025) and upper (0.975) percentile for the 100 simulations performed for each strategy. C = Consecutive months.

Ranking	Timing	Length	Pv Median	Pv Lower	Pv Upper
	No rodent		1,120,606	996,757	1,260,835
1	February-November	2	931,014	773,896	1,075,264
2	February-October	2	878,199	719,371	1,052,676
3	August-September-November	3	838,413	697,512	987,665
4	July-August-November	3	816,851	634,975	974,015
5	September-October-December	3	813,120	648,320	985,674
6	August-November	2	808,682	600,792	978,686
7	July-August-October	3	782,070	633,179	978,902
8	August-September-December	3	779,424	588,025	984,545
9	January-November	2	777,642	576,058	974,042
10	January-February-November	3	774,406	645,634	914,663
11	February-September	2	774,208	584,891	941,000
12	February-March-November	3	772,561	622,465	914,585
13	January-February-October	3	768,626	641,574	914,355
14	January-February-March-November	4	759,149	629,738	899,075
15	August-September-October-November	4(c)	757,621	629,512	898,085
16	February	1	755,790	527,945	916,108
17	February-March-April-November	4	755,471	605,827	896,872
18	August-September-October-December	4	755,415	624,990	896,990
19	September-October-November-December	4(c)	755,230	629,670	897,794
20	January-February-March-October	4	752,939	626,574	898,663
21	January-October	2	751,956	551,892	965,470
22	October-November-December	3(c)	750,987	551,225	938,758
23	July-August-September-November	4	750,177	616,460	897,797
24	February-March-October	3	749,394	606,719	912,442
25	January-February-September	3	747,689	602,444	913,508
26	January-February-September	3	747,689	602,444	913,508
27	January-February-March-July	4	746,972	565,505	865,316
28	June-July-October	3	745,252	599,947	922,673
29	June-July-September	3	744,767	603,183	900,971
30	June-July-November	3	743,836	553,709	930,108
31	September-October-November	3	743,690	492,283	957,366
32	July-August-December	3	742,479	429,528	933,755
33	January-February-March-May	4	741,988	565,998	880,496
34	January-February-March-June	4	740,971	566,001	880,511
35	July-October	2	738,160	569,848	916,392
36	January-February-March-August	4	735,696	579,369	890,672
37	January-February-July	3	735,593	538,167	874,845
38	February-August	2	735,325	542,019	956,210
39	February-March-April-October	4	735,046	591,536	897,825
40	January-February-March-September	4	732,365	614,741	898,324
41	January-February-March-December	4	731,242	565,821	885,662

Appendix 10: Continued

42	June-July-August-November	4	729.455	550.784	891,067
43	January-February	2	726.764	544.642	916,650
44	July-November	2	725,362	483.456	905,606
45	January-February-August	3	722.441	524.565	886,968
46	July-August-September-december	4	721.049	531.519	897.094
47	January-February-May	3	720.625	355.611	872,386
48	February-July	2	720.508	534,249	905,224
49	January-February-March-April	4(c)	720.296	530.595	864.457
50	July-August-September-October	4(c)	717.030	557.607	895.645
51	February-March-December	3	710.546	451.132	859.014
52	January-February-April	3	709.966	386.216	870.584
53	February-March-April-June	4	706.302	541.418	863.042
54	February-March-June	3	704.824	503.316	865.382
55	February-March-April-December	4	703.575	473.718	848.760
56	June-July-August-December	4	699.898	485.202	872.357
57	February-March-April-September	4	697.969	564.736	895.101
58	February-March-April-July	4	697.675	526.950	849.914
59	January-February-June	3	695.504	327.121	866.246
60	February-March-July	3	694.126	491.383	848.452
61	June-July-August-October	4	693.108	545.962	890.071
62	February-March-April-August	4	692.958	523.317	852.658
63	February-March-August	3	690.247	488.673	897.605
64	January-September	2	685.215	435.457	903.333
65	February-March-September	3	682.491	536.447	889.126
66	September-December	2	681.329	449.169	894.858
67	February-December	2	677.961	462.992	878.982
68	June-July-August-September	4(c)	671.845	546.759	880.305
69	August-September-Octomber-November-December	5(c)	669.178	544.601	809.017
70	January-February-March-April-November	5	669.135	540.164	809.248
71	February-March-April-May-November	5	668.596	516.720	809.063
72	July-August-September-October-November	5(c)	667.753	541.821	808.130
73	May-June-July-November	4	667.132	463.423	852.019
74	February-March-May	3	667.052	415.484	858.003
75	July-August-September-October-December	5	666.434	541.299	808.445
76	January-February-December	3	664.524	396.167	842.015
77	January-February-March-April-June	5	664.442	480.737	790423
78	January-February-March-April-May	5(c)	664.364	480.672	790.345
79	February-March-April-May	4(c)	664.142	477.401	843.079
80	January-February-March-April-October	5	663.573	536.365	809.165
81	May-June-July-Semptember	4	663.126	519.580	812.247
82	June-July-August-September-November	5	662.652	528.443	808.119
83	June-July-December	3	659.810	213.199	910.708
84	February-March-April-May-October	5	658.364	513.489	808.586
85	January-February-March-April-July	5	652.901	480.606	790.065
86	January-February-March-April-December	5	652.420	492.143	795.566
87	January-August	2	652.112	404.313	890.689
88	May-June-July-August	4(c)	651.490	515.804	798.880
89	February-March-April-May-December	5	648.988	462.049	787.795

Appendix 10: Continued

90	January-February-March-April-August	5	648.624	494.766	803.207
91	January-February-March-April-September	5	646.166	526.919	808.877
92	January-February-March	3	645.309	380.378	866.171
93	August-December	2	644.665	394.793	886.658
94	May-June-July-August-November	5	639.457	461622	801.882
95	February-March-April-May-August	5	638.000	479.039	794.647
96	May-June-July-December	4	637.610	418.936	825.376
97	February-March-April-May-September	5	636.166	506.275	807.983
98	June-July-August-September-December	5	635.657	500.858	807.992
99	January	1	635.110	447.532	834.015
100	September-November	2	631.529	396.851	921.494
101	February-March-April-May-June	5(c)	629.037	459.200	782.625
102	June-July-August-September-October	5(c)	628.336	468.625	806.432
103	February-March-April-May-July	5	625.575	452.164	764.755
104	August-September-October	3	623.736	394.024	931.260
105	May-June-July-August-December	5	612.962	457.858	787.555
106	April-May-June-July	4(c)	607.994	435.366	791.734
107	May-June-July-August-October	5	603.044	456.206	800.108
108	February-May	2	594.361	275.546	908.704
109	April-May-June-July-November	5	591.019	436.094	762.082
110	April-May-June-July-December	5	587.180	416.193	740.514
111	March-April-May-June-November	5	582.775	408.616	763.011
112	May-June-July-August-September	5(c)	582.582	456.869	790.231
113	February-March	2	582.097	408.468	765.691
114	March-April-May-June-December	5	575.817	398.938	738.466
115	February-June	2	575.681	364.530	871.387
116	April-May-June-July-September	5	573.566	424.860	722.191
117	March-April-May-June-July	5(c)	572.727	420.618	712.468
118	April-May-June-July-October	5	570.887	434.534	743.963
119	June-July-August	3	568.766	184.709	857.285
120	April-May-June-July-August	5(c)	567.922	430.117	711.413
121	March-April-May-June-October	5	561.925	400.679	744.591
122	March-April-May-August	4	410.657	43.407	746.436
123	July-September	2	407.600	173.803	720.631
	No Control		365.138	243.547	513.338
124	July	1	322.608	186.692	476.103
125	March	1	250.907	133.913	399.486
126	March-July	2	230.353	98.824	513.825
	Control in all the months throughout the year	12	37.512	-86.344	117.742