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The bioeconomics of controlling an African rodent pest species

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ABSTRACT. The paper treats the economy of controlling an African pest rodent, the multimammate rat, causing major damage in maize production. An ecological population model is presented and used as a basis for the economic analyses carried out at the village level using data from Tanzania. This model incorporates both density-dependent and density-independent (stochastic) factors. Rodents are controlled by applying poison, and the costs are made up of the cost of poison plus the damage to maize production. We analyse how the present-value costs of maize production are affected by various

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rodent control strategies, by varying the duration and timing of rodenticide application. Our numerical results suggest that it is economically beneficial to control the rodent population. In general, the most cost-effective duration of controlling the rodent population is 3–4 months every year, and especially at the end of the dry season/beginning of rainy season. The paper demonstrates that changing from today's practice of symptomatic treatment when heavy rodent damage is noticed to a practice where the calendar is emphasized, may substantially improve the economic conditions for the maize producing farmers. This main conclusion is highly robust and not much affected by changing prices of maize production.

1. Introduction

Rodents represent major pest problems worldwide, both in the countryside and in the cities. They do, for instance, cause serious damage to crops (such as cereals, root crops, cotton, and sugarcane) both before and after harvest. They also damage installations and are reservoirs or vectors for serious infectious diseases (Fiedler, 1988; Stenseth *et al.*, 2003).

In Africa, more than 70 rodent species have been reported to be pest species (Fiedler, 1988). Some of these exhibit irregular population dynamics with occasional explosions, typically occurring over extensive areas (Fiedler, 1988; Leirs *et al.*, 1996). Within eastern Africa, multimammate rats (*Mastomys natalensis*) are among the most important pest rodents (Fiedler, 1988). Damage during outbreaks is profound and significantly worsens the already unfavourable food situation on the African continent. The average rodent damage by the multimammate rat to maize in Tanzania has been estimated to be between 5 and 15 per cent yield loss, and for Tanzania this amounts to an average of approximately 412,500 tonnes per year (FAO statistics, 1998; Makundi *et al.*, 1999). This corresponds to what would be sufficient to feed more than 2 million people for an entire year (at about 0.55 kg/day/person) or represents an estimated value of almost 60 million US$ (September 1999 village market price in Tanzania, being around 14.5 US$ per 100 kg bag of maize). Eruptions of the multimammate rat population represent direct disasters for the subsistence farmers involved, but may also have national and even international political consequences. Panic-stricken authorities may initiate control operations – however, often too late and typically with quite poor results. There is thus a clear need to predict and, if possible, prevent such outbreaks of rodent populations (Mwanjabe, 1990; Leirs, 1999).

The control of pest rodents does, however, have both an ecological and an economic component interacting dynamically with each other so as to render intuitive reasoning difficult. In this paper we consider both the ecological and the economic components of rodent damage and control. This we do through the analysis of a bio-economic model – a model falling within the concept of ecologically based rodent management (EBRM) (see, e.g., Singleton *et al.*, 1999). We specifically evaluate the relations between control timing, control duration, and damage reduction. Our model is quite general; hence, our analysis may illustrate pest control involving rodents living in highly seasonally varying environments. The model consists of a well-established stage-structured ecological model (see Leirs *et al.*, 1997a; Leirs, 1999; Stenseth *et al.*, 2001) and is integrated with an economic model incorporating the crop damages by the rodents and the cost of controlling them.

The links between the ecological and the economic components are represented by the control measures affecting the mortality of the rodents as well as the rodents' damages on the maize crop. There is also a link through rainfall, there being both a seasonal and stochastic component, which affects both the rodent population ecology and the crop yield. The timing of the rodents' breeding season is strongly related to the annual distribution of rainfall (Leirs *et al*., 1993). In addition, rodent survival and maturation are affected by precipitation in the preceding few months, as well as density-dependent factors (Leirs *et al*., 1997a). Thus, rainfall influences the crop yield in two ways: positively through production since more rain (within limits) implies higher yield, and negatively through a higher net growth of the rodent population following rain.

Control strategies are evaluated in terms of present-value costs, integrating the control cost – increases in the amount of damage control and poison used – and the crop damage – increases in the number of rodents. Two temporal scales are included in the model, as the relevant time scale for rodent maturation and survival is one month, while crop harvesting and the economic benefits from harvesting typically happen once a year. The double time scale results in a quite complicated ecology–economy interaction, and the model represents an original contribution to the more general literature on the economics of pest control as well as providing important policy implications for managing and controlling agricultural production in an environment with pest populations, cf. the overview in Carlson and Wetzstein (1993). Only very few papers in the literature focus on vertebrate pest control problems with particular emphasis on small mammals. Hone (1994) summarizes a number of simple static pest control models, and presents some estimates of rodent damages as well as damages related to other mammals; see also Barnett (1988). Saunders and Robards (1983) provide detailed estimates of what the damage and economic losses were during a mouse outbreak in Australia and the costs of the control operations. However, in all these papers, there is no dynamic link between the economic considerations and the rodent population ecology, such as when a control strategy becomes economic efficient. This is also the case for Tisdell (1982) who provides a detailed study of the damages and control costs of feral pigs in an Australian context. The cost and benefit of feral pigs, causing damages on Californian rangeland, is also studied in a recent paper by Zivin *et al*. (2000). This problem is analysed within an optimal control framework, as they use a lumped ecological model and quite simple cost and damage functions. The analysis reported in this paper is to some extent inspired by this study, as our model is built around control and damage functions, interacting through the ecology. However, contrary to Zivin *et al*. (2000), we work with a stage-structured ecological model within a stochastic framework (rainfall) with more realistic, and complex, cost functions and a double time scale. Because of this complexity, the model is not formulated explicitly within an optimal programming framework. Instead we single out some reasonable main strategies and compare the present-value costs of these outcomes through simulations. However, as a foundation, and guide, for these simulations, a simplified version of the cost-minimizing model is formulated analytically.

In order to fix ideas, we consider a small village consisting of a number of individual farmers, and that the management problem is at the level of an agricultural officer who implements the rodent control strategy for a wide area. The model may thus be seen as a planning model, where the agricultural officer serves as the social planner. This social planner, presumably, will have a relatively long planning horizon and a fairly low discount rate (Dasgupta and Mäler, 1995). In a follow up paper, we will analyse what happens at the farm level when there is a shorter time horizon, and where each farmer typically does not obtain the full benefit of removing the pest from his farm; that is, externalities are present. Throughout the present paper, the ecological model is at the scale of one hectare. However, this does not mean that we literally assume that the village agricultural area is of the size of just one hectare. The area may be fairly large, justifying the assumption of no dispersal into the field when controlling the rats. One hectare is also the scale used for the agricultural benefit, as well as the costs of rodent control.

The paper is organized as follows. In the next section we briefly present some background material for the analysis. The ecological model is presented in section 3. In Section 4 the cost and damage functions of pest control are outlined, while the management problem and the various control strategies are formulated in section 5. The results of the numerical analyses are shown in Section 6.

2. The studied model system

As a basis for the analysis, we have used available insights on the multimammate rat population and their importance as an agricultural pest species, as studied in Morogoro, Tanzania, and elsewhere. In this region, 62 per cent of the active population are cultivators; the large majority of them being subsistence farmers. The predominant crop is maize, accounting for about 45 per cent of the hectarage under food crops and 32 per cent of the produced food crops (Anonymous, 2003). Irrigation is very rare and nearly all the maize crop production relies on rain. The rainy season in Morogoro is bimodal, with a first, but unreliable, peak between October and December and a second peak starting in February–March and continuing until May (Mwanjabe and Leirs, 1997). After the onset of heavy rains in February–March, fields are ploughed and prepared for planting. Hence, planting of maize seeds typically takes place in March, although the exact timing depends on rainfall. Planting is more or less synchronous in a large area within a period of a few weeks. Field sizes are small, about 0.5 ha per household. The crop yields in the region are very low with maize production averaging 1.5 tons per hectare, going up to 2.5 tons per hectare under improved agricultural conditions (Anonymous, 2003; see also figure A1).

Although we have developed the model with the multimammate rat in Morogoro in mind, the model and reasoning will also be applicable to other crop growing areas involving rodents living in highly seasonally varying environments and with an institutional and economic structure close to the one found in rural Tanzania.

Rodent damage typically occurs immediately after planting and until the maize seedlings have reached the three-leave stage (about 2–3 weeks after planting). When heavy rodent damage to the seedlings becomes obvious (about ten days after the original planting), farmers may decide to replant. However, we have simplified the setting for our model by assuming that planting always (and only) occurs in March and that damage caused by rodents is not remedied by replanting.

Harvesting occurs in July–August. If rainfall in October–December is very abundant, which rarely happens, then planting is possible in that season as well. However, farmers generally do not trust this first part of the rainy season, since it is very unreliable. Hence, even though planting may be possible, they are afraid that rainfall will not be sufficient during the rest of the growing season. Thus, planting in that season only happens in some years and even then only a part of the farmers decide to participate. Here we ignore such a second crop.

As noted in the introduction, we consider two, overlapping time scales: one for the ecological population dynamics processes and another for the economic processes. The economic yearly time scale relates to the fact that crop harvesting normally takes place once a year, whereas the ecological time scale is monthly. Since pest control actions may take place several times a year, the control costs will also be given with a time step of one month. However, these costs are accounted for once a year, and, as a result, collapse into the yearly time scale. We refer to the month by the index n (0, 1, ..., 11, 12, 13, ..., 23, 24, 25, ...) and the year by the index t (0, 1, 2, ...). Each month equal to 8, 20, 32, ... (i.e. August each year) corresponds to harvesting time and is defined so as to determine the beginning of a new production period, or 'cropping year'.

3. The population growth under pest control

The ecology is based on the model presented by Leirs *et al.* (1997a) and further explored by Leirs (1999), and Stenseth *et al.* (2001). Reproduction and survival parameters are governed by both density-dependent processes and density-independent processes (such as rainfall being treated as a time-dependent stochastic factor). The scale of the model is at one hectare, while the agricultural area considered may be quite large; hence, we ignore (as is typical within population dynamics modelling) dispersal. Our model further describes only the female part of the population; the demographic parameter estimates are more reliable for females than for males. Moreover, it is, after all, the female part of the population that is instrumental in generating the population dynamics through reproduction, which is typically limited by the number of breeding females. The ecological model is a stage-structured model (see, e.g., Getz and Haight, 1989, for a general overview) with four stages, and where the vector $\mathbf{N}_n = (N_{j0,n}, N_{j1,n}, N_{sa,n}, N_{a,n})$ 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)

$$\mathbf{M} = \begin{bmatrix} 0 & 0 & 0 & B\left(V_n, N_n^{(e)}\right) \\ s_{0n} & 0 & 0 & 0 \\ 0 & s_{0w} & (1-m_n)\cdot s_1\left(V_n, N_n^{(e)}\right)\cdot\left(1-\psi\left(V_n, N_n^{(e)}\right)\right) & 0 \\ 0 & 0 & (1-m_n)\cdot s_1\left(V_n, N_n^{(e)}\right)\cdot\psi\left(V_n, N_n^{(e)}\right) & (1-m_n)\cdot s_2\left(V_n, N_n^{(e)}\right) \end{bmatrix}, \tag{1}$$

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 sub-adult 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 $N_n^{(e)} = N_{sa,n} + N_{a,n}$ (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-adult and adult; 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 maybe 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-month 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 the Appendix, table A1.

Notice that rodent demography is not directly affected by crop production; the link is indirectly through rainfall. Moreover, crop production as such has little effect on the rodents: they damage planted seeds (i.e., before crop production has started) and then the ripening seeds at harvest time, but, at that moment, the amount of available seeds is much larger than can be consumed by the rodents, even in poor harvest years. During the crop growing period, the rodents do not damage the crop but live from alternative food in and around the fields (Makundi *et al.*, 1999).

Stenseth *et al*. (2001) have explored how this 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 (i.e., control every month), 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 a large increase in mortality.

Our 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 assume that precipitation has a negligible effect during the current month. In addition, we make the reasonable assumption for the Tanzania multimammate rat system 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 the same month (and given by X_n).

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

$$m_n = m(X_n). \tag{2}$$

The reduction in natural survival, being in the domain [0, 1], is therefore given as $\partial m/\partial X_n \geq 0$ with $m(0) = 0$.

4. The costs and damages

The costs of rodent control consist of two main components: the direct cost of controlling the rodents and the cost through reduced yield. We start with the yield damage cost. The crop is maize, and the yield depends on the quality of the agricultural land, labour input, fertilizer use, and rainfall (see, e.g., Ruthenberg, 1980 and McDonagh *et al.*, 1999). Assuming one crop per year (see above) and assuming that all production factors, except water, are optimally utilized and assumed fixed throughout the analysis, the yield in kg per ha of agricultural land in the absence of rats may be written as

$$Y_t = Y(A_t) \tag{3}$$

where A_t is the amount of rainfall accumulated throughout the maize-growing season (i.e. precipitation during the five months prior harvesting, typically in August, see above). $Y(A_t)$ is generally increasing in A_t up to some threshold level, but at a decreasing rate; i.e. $\partial Y/\partial A_t > 0$ and $\partial^2 Y/\partial^2 A_t \leq 0$ (McDonagh *et al.*, 1999). In addition, no rain means a small and negligible harvest, hence, $Y(0) = 0$.

Damages caused by the rats are composed of two components, one relating to the damage taking place during planting, expressed as a fraction of the yield, and another one relating to the damage through direct consumption of grain during harvesting, measured as absolute yield loss. Between planting and harvesting, there is essentially no damage caused by the multimammate rat (Makundi *et al.*, 1999). The fraction of maize planted in month n that is damaged is directly related to the abundance of rats; that is

$$D_n^p = D^p(N_n) \tag{4}$$

with $\partial D^p / \partial N_n > 0$.

Assuming no further rodent damage, the annual maize damage will then be $Y(A_t)D_n^p$. However, there will be a further reduction during the harvesting period. The harvesting damage, measured in absolute loss (kg per ha), is also assumed directly related to the rodent abundance

$$D_n^h = D^h(N_n), \tag{5}$$

with $\partial D^h / \partial N_n > 0$ and $D^h(0) = 0$. Consequently, the actual loss in maize production in year t is

$$D_t = \max\{Y(A_t), [Y(A_t)D^p(N_{n-t}) + D^h(N_n)]\} \tag{6}$$

where the time lag τ, the length of the maize growing season (typically five months), is introduced to scale the two types of damages occurring in different months. The economic crop loss per ha and year is therefore given as

$$K_t = pD_t \tag{7}$$

where p is the price of the crop, assumed to be fixed over time.

The direct control cost reflects basically the purchasing cost of the poison. There may also be some 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. The control cost function at time n (i.e., month), assumed to be fixed over time, is therefore assumed given as

$$C_n = C(X_n) \tag{8}$$

with $\partial C / \partial X_n > 0$ and $C(0) = 0$.

Having defined the control and damage cost functions, the total cost in year t reads

$$Q_t = K_t + \sum C_n \tag{9}$$

where the summation of the control cost is taken over the year; that is, $n = 8$ to 19 to cover the year $t = 1$, etc. (see above). Equation (9) implies that the effect of discounting within the year is neglected. The total cost function also neglects, if any, negative poison effects on crop production. Environmental costs caused by the poison are not taken into account.

5. The management problem and the control strategies

While the crop without damage and the control cost one year is invariant of the crop yield without damage and control cost for the previous year, this is obviously not so for the crop damage. Through the damage and control use, the crop loss for one year is contingent upon the ecological state of the system in previous years. Hence, the cost in various years is linked together through the size of the rodent population. The stochastic nature of the problem also makes a link through time as the rodent control considered refers to an environmental situation were both the crop yield and the rodent population growth are subject to large fluctuations since rainfall is largely stochastic.

The management problem is therefore dynamic, and the various management strategies, given by a time sequence of the control X_n, either zero or non-zero, is evaluated by calculating the median of the present-value cost

$$PC = \sum_{1}^{T+1} \frac{Q_t}{(1+\delta)^t}, \tag{10}$$

together with the variability (more details below). T is the control (planning) horizon in years, and δ is the (yearly) rate of discount. The basic trade-off at month n, as well as over time, is hence between the control cost, increasing in the amount of poison used, and the crop damage, decreasing in the amount of poison used, and where the interaction goes through the survival rate m_n of the rats.

Because of the complexity of the ecological model containing four stages of rats, the stochastic nature of the problem and the complicated ecology–economy interaction due to the double, and partly overlapping, time scale, it is impossible to obtain any analytical solution of the management problem. However, when disregarding the stochastic element, ignoring the double time scale and replacing the model (1) with a biomass model, the basic economic trade-off may be illustrated. Under these simplified assumptions and hence writing the population growth as $N_{n+1} = G(N_n, X_n)$, where G is the natural growth function with $dG/dX_n < 0$ so that N_n represents the number of 'normalized' rats at time n, it is shown in the Appendix that the control condition

$$\partial C(X)/\partial X \geq \lambda[\partial G(N, X)/\partial X] \tag{11}$$

holds.

The interpretation of the control condition is that the marginal cost of the control, when economically rewarding to use it, should be equal to the marginal value of damage avoided by the control, evaluated at the shadow price $\lambda < 0$ of the rodents. And, on the contrary, when it is not economically beneficial to use control, the marginal cost should be above the marginal value of the damage avoided. The shadow price changes through time, meaning that the damage cost avoided by the control changes through time as well. In the simplified model (again, see the Appendix) it may settle down to a steady-state value, but that will definitely not happen in the full model, not at least because of the fluctuations of the crop yield and rodent population due to the stochastic rainfall.

Based on the above reasoning, we now single out some main strategies for controlling the rats that will be utilized in the numerical simulations. Consistent with current practice in the rural areas in Tanzania (Mwanjabe and Leirs, 1997), we assume that X_n, when applied, is fixed at some level. Keeping the dosage of the poison per application fixed, we are therefore not considering how much poison to use; strategies are formulated in which month to apply the control measure (the timing), and for how long (the duration). We further assume the control, being either zero or non-zero in a specified sequence of months over the year, is the same from year to year.

The most trivial strategy to test is one in which rodent control is never applied, either because of lack of resources to apply rodenticides, or because it may be believed that the damage avoided by applying control will not outweigh the cost of the rodenticide application. The more common strategies, however, are to apply rodenticide just before or soon after planting, or just before harvesting, or attempting to keep rodent population levels low throughout the maize growth season. These strategies aim at immediate effects. Focusing on the negative shadow value of rodents, an alternative long-term strategy could be to apply rodent control during the reproductive season, so as to minimize the birth of new animals. Again this could be done early, late, or throughout the reproductive season. Finally, rodent control could target the population at its usual peak late in the year, maximizing the number of rodents that would be killed.

Altogether we consider the following control strategies X_n, being either zero or at a fixed nonzero level, related to the calendar, and repeated in the same way every year:

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, we have combined the above strategies with various conditions related to the state of the system (such as conditioning the application of poison on rodent density or precipitation). As indicated above, today's practice in Tanzania consists mainly of symptomatic treatment when heavy rodent damage is noticed. In some cases, depending on the visible presence of many rats or issued outbreak warnings, farmers may choose to organize a prophylactic treatment at planting time. Such practices will be included in our analysis, basically to compare the present practice with other, and better, strategies.

6. Results

Specific functional forms and the data

The specific functional form of the control function (2) used in the numerical simulations neglects any influence through the size of the rodent population. Moreover, for the given dosage X_n, we assume that the combined effects of natural mortality and the rodenticide-induced mortality are constant and always 0.90. This is consistent with the field experience of rodent control officers in Tanzania; the used poisons are effective in killing rodents and at the used quantities they should be more than sufficient to kill all rats in the field. Usually, however, about 10 per cent of the rodents in a field survive the rodenticide application because they do not eat the bait, either accidentally or because they avoid it (Mwanjabe, personal communication). Hence, with reference to the population dynamics (1), $(1 - m_n)s_i(V_n, N_n^{(e)}) = 0.10$ is fixed every month when rodenticides are applied, and $s_i(V_n, N_n^{(e)})$ in other months (see below and table A1 in the Appendix for further details).

Figure A1 in the Appendix gives the maize yield function. It includes the use of fertiliser of 40 kg/ha, which is used and kept fixed throughout the simulations. The damage function during planting is specific as $D_n^p = a + bN_n/(c + N_n)$, where a represents the background death rate of young maize plants (i.e. germination failure 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 Appendix (table A2) gives the parameter values. The damage function during the harvesting period is further specified linear, $D_n^h = dN_n$, and where the value of d is based on information about the daily food consumption of rats (again, see the Appendix for more details). The direct cost function is assumed to be linear as well, $C_n = wX_n$, with w as the purchasing cost of the poison (see above). X_n is fixed either at zero or at some non-zero level (see above), and if applied, typically a treatment will be carried out with 2 kg of poisoned bait per ha.

As baseline value for the crop price we use $p = 100$ Tsh/kg maize, and $w = 6500$ Tsh/kg poison as the unit the control cost (table A2). The effects of changing economic conditions will, however, be studied. The management problem is, as mentioned, considered 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, while the rate of discount δ should reflect the social one. In the basic scenarios, we use $T = 10$ years and 7 per cent rate of discount, $\delta = 0.07$.

Since rainfall patterns are a major component of the model's variability, simulations have been run with a large number of different rainfall series.[1] We use monthly rainfall values (Meteorological Station, Morogoro, Tanzania) that were drawn from rainfall data obtained for that particular month in the period 1971–1997; that is, for each month of the run, and independently from the values for the other months, we choose a value at random from the 27 years for which we had values for that month. For each control strategy, and set of model parameters, the model was run 100 times, each time with a different random seed, 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. In order to reduce the effect of initial conditions, each model run ran for 248 months before pest control and economic evaluation started; it then continued for a number of years, reflecting the given planning horizon, T. Accordingly, the evaluation of each control strategy is done by calculating

[1] The model was implemented numerically using *Stella Research, version 5.1.1* (High Performance Systems, Inc., Hanover, NH, USA).

the median present-value cost (PC) of equation (10) for the 100 runs, together with the variability, given by the 95 per cent range values.

The structure of the analyses
To see the basic logic of the numerical simulations, figure 1 provides four examples based on two rainfall series and two different control strategies: control applied once a year in February (just before planting), and no control at all. The two panels A and B are for different (random) rainfall series, chosen from different runs of the model; the examples are representative of the general pattern. As can be seen, under the rainfall pattern in panel A, the rat abundance is subject to large fluctuations, both with and without control. However, the actual yearly harvest loss D_t is quite high accompanied by high values for the total current cost Q_t when applying no control, whereas under the February control the yield loss is smaller and the current cost is lower. The same broad picture, at least for the total current cost, is also provided in panel B.

For the given fertilizer use and the baseline values for the maize price and poison cost, these results clearly indicate that pest control is economically rewarding, as the average yield loss is smaller and the current cost and, hence, also the PCs (not shown) are lower when control is carried out. Of course, care must be taken as figure 1 exhibits only two runs for each strategy. We now turn to the full-scale simulations where the results present the median PCs, together with the variance, for 100 simulations within each strategy shown.

Duration and timing of the control
Figure 2 summarizes the results where we have simulated the application of pest control for different numbers of consecutive months. The duration of the control (i.e., number of consecutive months) is indicated along the horizontal axis, where altogether we have included seven months as the rat population goes close to extinct beyond four months (see below). No control at all is included as well, indicated by the number 0 along the axis. For each number of months applying control, except no control at all (0), there are 12 possible months to start controlling. Hence, we have generally 12 medians and 95 per cent range plots within each possible duration of control as indicated by JFM . . . ND (January, February, Mars . . . , November, December). The upper panel represents the median present-value cost (PCs) with bold points, and the 95 per cent range with thin vertical lines. The PCs without rats at all are also shown, displayed as its 95 per cent range variation as the shaded area. The lower panel gives the number of rodents at the end of the planning horizon, also as median and 95 per cent range values.

From the upper panel in figure 2, three main features should be noticed:

(1) The median present-value cost is high without control (0 months), but decreases in general for strategies with up to four consecutive months of control, beyond which the present-value cost (PCs) starts increasing. Hence, the patterns only up to seven consecutive months are displayed. A rewarding strategy is therefore clearly to control the rats for some months, but not for too long.

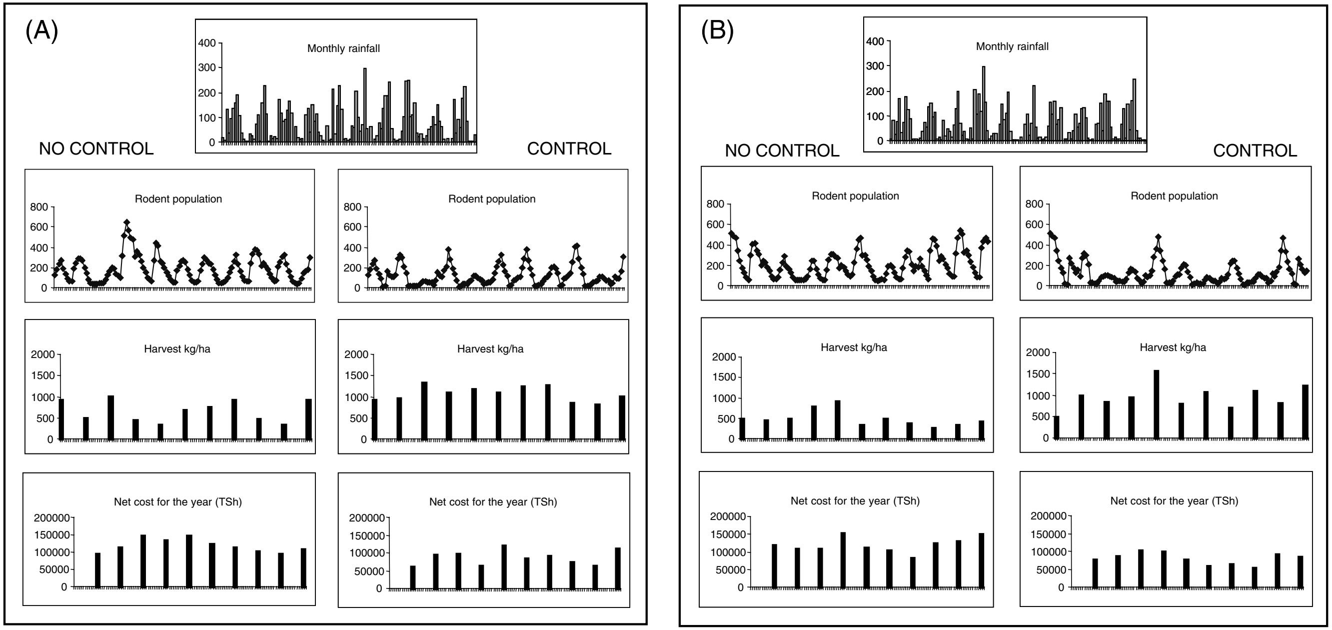

Figure 1. *Four examples of model runs. Panel A and B for different (random) rainfall series. Two different control strategies; no control and control applied once a year in February*

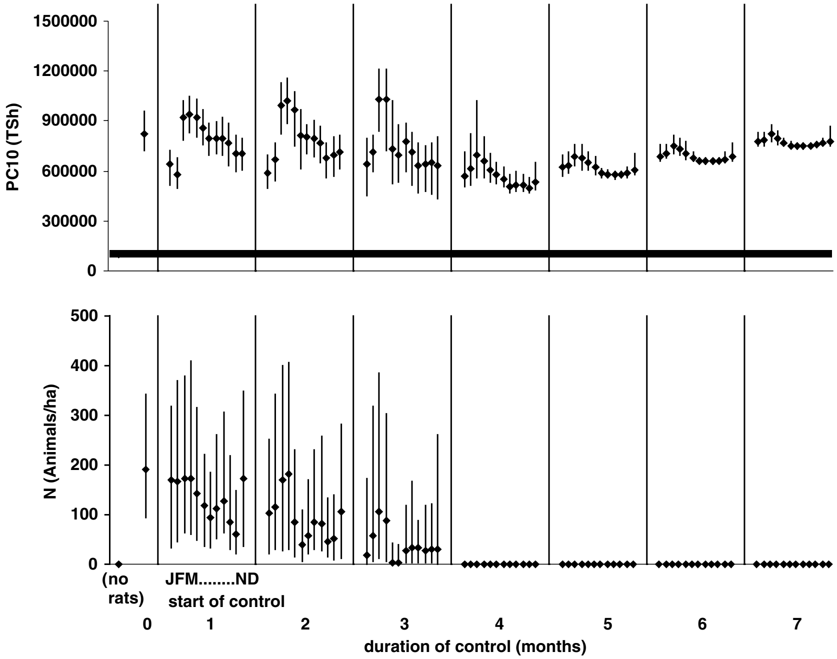

Figure 2. *Results when control applied for a different number of months and various timings. The duration of the control for number of consecutive months along the horizontal axis (up to seven months). For each number of months applying rodent control (except 0) there are 12 possible months when to start controlling. The first set of values along the vertical axis are for starting control in January, the second for starting in February, and so on until the last starting in December. Upper panel: the median present-value cost PC (with a planning horizon of ten years from the beginning of control) with bold points, and the 95 per cent range with vertical lines. The shaded area PC shows the median (95 per cent range) in a hypothetical situation without rodents. Lower panel: the number of animals per ha at the end of the planning horizon. Note, however, that for four months of pest control, the rodent population does not always become completely extinct, but is not visible at the scale of the figure (<1 animal/ha)*

(2) It is more profitable to control during certain months than during others. If poison is applied one or two months every year, it seems most rewarding to start controlling in January/February, whereas if poison is applied for three to five months, it is most rewarding to start controlling in August–December/January.
(3) There are small differences, both in term of median value and variability, between the most economic rewarding strategies.

Under the baseline economic conditions, the most rewarding strategy is to apply poison during four consecutive months starting in November, but many of the other strategies shown in figure 2 do not result in a significantly higher PC. Strategies having significantly higher median PCs include controlling for one month, and from eight up to 12 months (the last ones not shown in the figure). Some of the strategies for five and more consecutive months may give lower PCs than strategies applied for, say, two and three months (see also below). Strategies having significantly higher PCs also include applying controls for two to three months during the cropping season (i.e., starting in March). The timing of the control period seems therefore to be more important than its duration, especially for control periods of three months or less. Hence, poisoning will be most rewarding just before the growing season, so as to reduce the number of rodents before the planting of maize. Generally, the variability of the PC increases up to three months duration of the control. After that it decreases again slightly and stays more or less constant for five months and longer duration of control. Thus, the economic outcome of control during three months or more is less uncertain than with shorter periods.

The lower panel in figure 2, presenting the rodent population at the end of the planning horizon, shows that some of the strategies applying rodent control for one to two months each year do not affect population development very much. However, if the duration of control is more than three months, the rodent population reduces slowly towards extinction, and faster for longer duration of the control. The population goes close to extinct at the end of the planning horizon after four consecutive months. Hence, these graphs clearly indicate that control for more than four months is not economically meaningful, as more control means more control costs, but no further reduction in the number of rats, and hence, no further reduction in crop damages. It is important to notice that the patterns in the upper and lower panel are not concurrent, i.e. a small number of rats may coexist together with high PCs and vice versa, showing that the relation between numbers of rodents and economic benefit is not a trivial one. Notice also the high population variability.

Other control strategies

For all results presented so far we have applied rodent control during consecutive months and always during these months. However, the economic benefit of using pest control might be higher if we split the control months into two (or more) periods each year separated by at least one month. We tested this for two control periods each year with a total of 2 (1 + 1), 4 (2 + 2), 6 (3 + 3) and 8 (4 + 4) months. For these simulations, the present-value costs (PCs) were generally lowest when rodent control was used during three months separated by at least one month. Hence, we also tried all possible combinations of 3 (1 + 2), but also 4 (1 + 3) months separated with at least one month. The 20 most rewarding strategies of duration and timing of rodent control are presented in table 1. As can be seen, combinations of three to four months control in the period before the start of the cropping season are still the most rewarding, together with a two months control in February and November, There are, however, no significant present-value cost differences between the 20 strategies shown in the table; all strategies fall within the range of about four to five times the PC of the hypothetical case of no rodents at all. Still, compared to no control at all (the bottom line), there are clear differences.

We also investigated whether an upper or lower threshold value on precipitation or rodent density before applying poison could affect the

Table 1. *Ranking of the 20 most economically 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 no control (lower line) included as well. Present-value cost PC (in Tsh) 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*

			PC		
Rank	*Timing*	*Length*	*Median*	*Lower*	*Upper*
	No rodents		103474	92073	115413
1	Jan, Feb–Nov	3	430300	393791	511020
2	Feb–Oct, Nov	3	442571	388248	512664
3	Jan, Feb–Oct, Nov	4	447360	389589	507799
4	Feb–Nov	2	450794	347518	530243
5	Jan–Oct, Nov	3	453333	394788	555138
6	Feb–Nov, Dec	3	460922	397604	549869
7	Jan, Feb–Oct	3	474188	397287	594848
8	Sep–Nov, Dec	3	492038	399272	662488
9	Nov, Dec, Jan, Feb	4 (c)	502887	474022	566226
10	Aug, Sep, Oct, Nov	4 (c)	506623	474321	577003
11	Jul, Aug–Oct, Nov	4	508180	480850	556699
12	Sep, Oct–Dec, Jan	4	508471	472771	567555
13	Oct, Nov, Dec, Jan	4 (c)	510735	477732	579215
14	Feb, Mar–Oct, Nov	4	511824	479538	600067
15	Aug, Sep–Nov, Dec	4	514175	469007	572573
16	Sep, Oct, Nov, Dec	4 (c)	514175	469007	572573
17	Jan, Feb–Sep, Oct	4	517276	480866	587799
18	Feb, Mar–Nov, Dec	4	518129	479457	582448
19	Jul, Aug–Nov, Dec	4	530267	479937	609263
20	Dec, Jan, Feb, Mar	4 (c)	530743	484888	647072
	Never control	0	820958	723460	956967

sequence of the most economically rewarding strategies. The only way a threshold value lowered some of the PC results, was if we applied control for four months or more with a very low threshold value on rodent density (threshold value = 5 animals/ha for 4 months, 10 animals/ha for 5 months or more). Such a low population density is, however, hardly possible to estimate reliably; hence, this is not a very applicable strategy.

The economic consequences of symptomatic treatment were also studied. As already indicated, today's practice in Tanzania represents an *ad hoc* approach, and typically poison control is applied when observed damage is high during planting season, or just before harvest. This practice was simulated by introducing a density dependent control in March and July. Various threshold values were tried, and the median PC values fell within the interval of about 830,000–856,000 Tsh when observing 100–200 rats per ha. Hence, these values are almost double the most promising control practices reported in figure 2 and table 1. Under the present baseline price values, these strategies were even worse than the option of no control at all (table 1).

Variations in the maize price and control cost
A permanent negative shift in the producer price of maize, p, will generally make shorter duration of the control relatively more profitable. The intuitive basis for this result is straightforward, as lower marginal crop damage cost must be compensated by lower marginal control cost (i.e. reduced duration of the control). On the other hand, the effect on the timing is quite modest. The economic conditions for the farmers may also be less favourable due to more expensive poison, and a positive permanent shift in w also leads in the direction of shorter duration of the control being relatively more profitable. Hence, instead of four months, five months, and one month duration per year being the most economically rewarding strategies under the base-line assumptions, we find that doubling the poison price makes duration of one month, two months, and no control the most economically rewarding strategies. Thus, more expensive poison means that more rats and a higher level of crop damage will be accepted in the best strategies (cf. also inequality 11 above).

The economic consequences of symptomatic treatment were also studied under shifting price and cost assumptions. All the time, the best practices compared to today's practises of introducing density dependent control in March and July were typically about half as costly. Finally, we also studied the effects of reducing the planning horizon and making the problem more myopic by setting $T = 5$ years. The rate of discount δ was also reduced. Generally, there are small changes taking place (not reported here). This was also so for an increased planning horizon and a higher rate of discount.

7. Discussion

Throughout this paper, we have considered a rodent pest problem where the management is in the hands of a social planner and where the agricultural area can be quite large. The control problem is specified as timing and duration strategies, where the dosage of the poison is kept fixed per month whenever poison is used (consistent with recent practice in Tanzania). The most economically profitable control period seems to be just before the planting season. The damage at planting accounts for such a large portion of the total losses due to rodents that minimizing the population during that short period is enough to reduce yield losses. Controlling for a longer period will reduce rodent populations at a time when they do not damage the crop anyhow, and, due to the very high reproductive capacity of the rodents, the population will increase rapidly as soon as control operations are stopped, repressing any long-term effects. The simulations, however, only indicate small profitability differences among various combinations of control months towards the start of the planting season. Although we have not valued environmental costs of the use of poison (see, e.g., Carson 1962) and negative impacts, if any, upon crop production are neglected, the small differences between the best strategies strongly suggests opting for a strategy amongst these that uses the least poison. Hence, taking environmental economic considerations into account, one month or two months of control just before the planting season, January and February, or eventually in November and February, seem to be the best overall strategies.

These economically most rewarding strategies differ significantly from today's practice of symptomatic treatment when heavy rodent damage is noticed. The economic threshold concept and the idea of adjusting the timing of pesticide use to pest density is an old one (Carlson and Wetzstein, 1993), but works poorly here because of the high reproductive rate of the rats and the short period after sowing during which most of the damage is done. Hence, the present paper demonstrates that shifting from such practices to more mechanistic control strategies; i.e. emphasizing the calendar instead of the pest abundance, can substantially improve the economic conditions for the maize producing farmers in the present case of multimammate rats. The best practices compared with today's symptomatic treatment will typically halve the sum of control and damage cost. The question of how to choose between an economic threshold model and a mechanistic control model is of general interest and should be examined further, but following our analysis it seems to be population growth characteristics of the pest rather than its taxonomic status that should govern that choice (see also Regev *et al.*, 1976).

We also find that permanent changes in the crop price and control cost give effects that are more or less in line with intuition. A less valuable crop and higher poison cost make shorter duration of the control and, hence, living with more rats and nuisance relatively more profitable. On the other hand, the optimal timing (i.e. in which months to apply poison) is only modestly affected by such changes. Consequently, it seems that the optimal timing is more closely related to the ecology and the abundance of rats than prices and costs, while the economy plays a more important role when it comes to the optimal duration of the control. One reason for this may be that the damage effect is far more important during some parts of the year, e.g. just before planting.

Throughout our simulations, we interpreted the pest control problem as taking place at the village level, where an agricultural officer serves as the social planner. While it mostly will remain the individual farmer's decision to apply control on his fields, the agricultural officer indeed plays an important role. His advice will be very influential not only to farmers, but also in ensuring timely access to rodenticides; in village shops, shelf-life of these poisons is limited so usually only limited quantities are available locally. The social planning horizon is also relevant because in case of an outbreak coming through, the government will be required to organise costly emergency measures (Makundi *et al.*, 1999). When making the problem more myopic through a reduced planning horizon, however, we find that the results are only modestly influenced. For the more myopic African farmer, when neglecting externalities due to various control practices within the management area, the above findings therefore also basically hold. When interpreting the results at the farm level, it should also be noticed that subsistence farmers frequently face credit restrictions, and, typically, for such farmers, there is cash only for seed (see, e.g., Dasgupta and Mäler (1995) for a general discussion). This has implications for fertiliser use which, however, has been kept fixed at a positive level throughout the analysis.

Models are only an approximation of how we conceive reality, and they are only as good as the assumptions on which they are based. Regarding our population model, the basic building block of the present analysis, two major assumptions do not hold in reality. The first one is that the model uses discrete time steps of one month; however, a lot can happen in a rodent population in one month. Secondly, our model does not yet include immigration processes but it is obvious that these can play an important role, particularly when the densities after rodent control have become much lower than in the surrounding fields. In such cases, a population may even be capable of recovering from a rodenticide application in the course of a few weeks (see, e.g., Leirs *et al*., 1997b), thus reducing the efficacy of control actions considerably. Regarding the agricultural activities, our model does not yet include the common practice of replanting after rodent damage, sometimes in combination with rodenticide application, and thus partially remedying damage. The crop price and the control costs are also kept fixed throughout the planning horizon, and the maize price is assumed to be the same in years with poor and good harvest. For all these reasons, the results should be interpreted very cautiously and the model is not yet ready to be confronted with farmers and taken into practice. However, the main finding of the above analysis, emphasizes that the calendar instead of pest abundance when controlling the rats will probably hold under more realistic assumptions and is clearly an application rule that is quite easy to implement.

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Appendix

The simplified management model

When using a continuous time approach, the current value Hamiltonian of the (strongly!) simplified management problem reads $H = -\{p[Y(A)D^p(N) + D^h(N)] + C(X)\} + \lambda[G(N, X) - N]$. The control condition reads

$$\partial H/\partial X = -\partial C(X)/\partial X + \lambda[\partial G(N, X)/X] \leq 0 \qquad \text{(A1)}$$

while the portfolio condition is

$$d\lambda/dt = \delta\lambda - \partial H/\partial N = \delta\lambda + p[Y(A)(\partial D^p(N)/\partial N) + \partial D^h(N)/\partial N] \\ -\lambda\,[\partial G(N, X)/\partial N - 1]. \qquad \text{(A2)}$$

The control condition holds as equality when it is optimal to use control; that is when $X > 0$. (A1) directly gives condition (11) in the main text. The portfolio equation governs the time path of the shadow price λ of the rodents, and all the time we have $\lambda < 0$, as the rodent is a pest and nuisance.

Table A1. *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., 1997a)*

Regime definition							
Rainfall in the past 3 months (mm)	V_n	<200	<200	200–300	200–300	>300	>300
Density per ha	$N_n^{(e)}$	>150	<150	>150	<150	>150	<150
Demographic rates							
Net reproductive rate	$B(V_n, N_n^{(e)})$	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
Sub-adult survival	$S_1(V_n, N_n^{(e)})$	0.629	0.513	0.682	0.617	0.678	0.595
Sub-adult maturation	$\psi(V_n, N_n^{(e)})$	0.000	0.062	0.683	0.524	0.155	1.000
Adult survival	$S_2(V_n, N_n^{(e)})$	0.583	0.650	0.513	0.602	0.505	0.858

The data

Table A1 summarises the demographic parameters in the ecological model. The specification of the demographic effect of the pest control equation (2) is problematic since it should include the effect of the rat abundance. Moreover, not discussed in the main text, it should also include the combined effects of natural and poison-induced mortality and the immediate effect of the latter on the former (through density-dependent mechanisms). Such information for a more detailed and realistic description

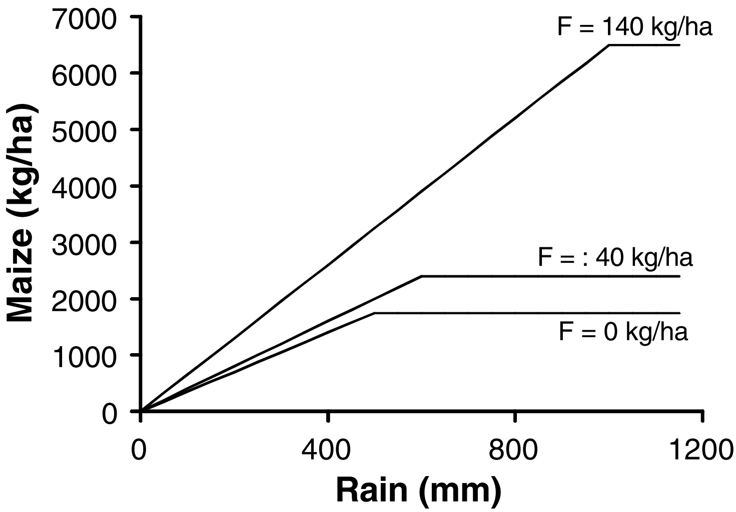

Figure A1. *Maize yield functions, dependent on the amount of nitrogen-fertilizer applied and rainfall during the growing season (adopted from McDonagh et al., 1999)*

of the control function is not yet available. We are collecting more detailed information about the control function, but for now, we have used the very specific function assuming that the total mortality under application of rodenticides is always 0.90.

Figure A1 gives the maize yield function (depending on rainfall and fertiliser use). The empirical evidence on fertiliser use is restricted, and data on fertiliser use beyond 140 kg/ha are lacking. All the time, 40 kg/ha is used.

The parameters of the crop damage function during the planting season $D_n^p = a + bN_n/(c + N_n)$ are given in table A2. The establishment of this function, based on a very detailed set of field data from Morogoro, Tanzania, is presented elsewhere (Mulungu *et al.*, 2002). The crop damage function during the period just before harvesting $D_n^h = dN_n$ is based on the theoretical consideration that a small rodent on average has a daily food intake of approximately 10 per cent of its body weight (Petrusewicz, 1970). Since Mastomys natalensis rats weigh on average 45 g during the pre-harvesting period (Leirs, 1995), since rodent damage to ripening maize cobs starts approximately one month before harvest and assuming that rats climbing the stalks spill or damage about the same amount as what they actually eat, the parameter d was set to be $d = 30$ days $\cdot$ 4.5 g/day $\cdot 2 = 270$ g. The length of the maize growing season τ is five months from planting to harvesting, as is usual in Morogoro, Tanzania, with the locally used maize varieties. When applying crop damage function at planting or harvesting time, we always doubled the calculated rodent population size N_n since the model only represented the female part of the population.

Table A2. *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 poison	w	6500 Tsh/kg
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

The price of the maize crop production, p, and the per unit poison price, w, refer both to 1999 market prices in Morogoro. The price for the poison is based on a bromadiolone bait poison. The parameter values used in the baseline simulations are given in table A2.